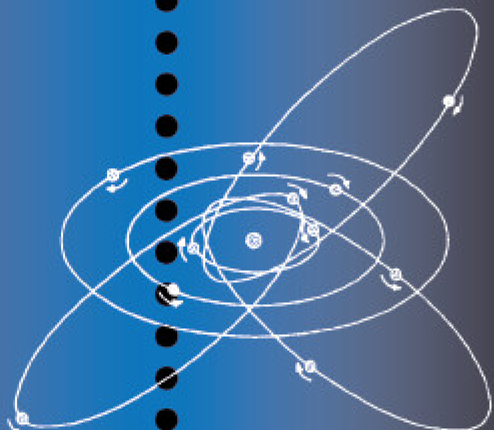
William A. Wallace

The Modeling of Nature

Philosophy of Science and Philosophy of Nature in Synthesis



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Preface

The basic insight behind this volume must be credited to Aristotle, the "Father of Western Science," in whose *Physics* we first find formulated the ideal of a scientific study of nature. The insight is that the human mind, contrary to the teaching of the skeptics of Aristotle's day, is capable of transcending the limitations of sense and of grasping the natures of things. To succeed in this quest it is endowed with a special capability, namely, that of reasoning from the more known to the less known, from the clearly perceived appearances of things to their hidden but intelligible underlying causes. In some cases, as when trying to penetrate into the material substrate of the universe—what Aristotle was to call "protomatter" (*hulē prōtē*)—the mind must reason by analogy (*kat' analogian*) and settle for a type of proportionate understanding.[1] To use the modern idiom, in foundational quests one must employ modeling techniques to penetrate into nature's secrets. This portion of our insight, only recently recognized by many philosophers, is signaled in our title, "The Modeling of Nature."

The modeling here suggested is not of a kind with a model one might construct to predict the weather, to make an economic forecast, or otherwise to achieve a practical result, granted that it has elements in common with them. Rather the intent is more speculative, theoretical, at ground epistemological—what might be termed "epistemic." The meaning is that conveyed by the Greek *epistēmē*, Aristotle's term for knowledge that is genuine knowing and thus to be differentiated from opinion (*doxa*). When individuals have an opinion on a matter they *think* they know, and yet they really do not know, for they allow that the contrary to what they hold might be true. But when they know scientifically—and,

1. *Physics*, Book 1, chap. 7, 191a8: "As for this underlying nature [protomatter], it is knowable by analogy."

for Aristotle, "epistemic" knowing is the same as "scientific knowing"—they are certain of the object of their knowledge, and this precisely because they know it through the causes that make it be as it is.

The difference between opinion and science, or epistemic knowing, assumes importance in contemporary philosophy because of a serious situation that has developed regarding the natural and human sciences. Part of the problem derives from the Scottish empiricist David Hume, who embraced a type of skepticism that denied to the human mind the ability ever to grasp a causal connection. Part of it derives from the German idealist Immanuel Kant, who extended Hume's line of reasoning to propose a more extreme agnosticism: the human mind is radically incapable of knowing things as they are in themselves. Both positions are difficult to reconcile with the advances made in the study of nature during the nineteenth and twentieth centuries, and yet whole generations of philosophers have found themselves blocked by Humean and Kantian *aporiai*. As a consequence, in the present day there are few proponents of a realist epistemology that is capable of vindicating science's knowledge claims. The logical empiricist phase of the mid-twentieth century registered the most serious failure in this regard. Perhaps it is not surprising that relativism and pragmatism have now become the dominant movements, with science seen as "justified belief" at one extreme or as myth and rhetoric at the other, but with all agreed that it can no longer be differentiated from opinion. Science too is fallible and revisable, ever incapable of arriving at truth and certitude.

Such a view of science, and its consequent appraisals of their results, would have scandalized Galileo Galilei and Sir Isaac Newton, the "Fathers of Modern Science." Obviously it calls into question not only their contributions but even the reality of the Scientific Revolution, for in this view that great historical event produced only a plausible way of looking at things, ultimately devoid of epistemic value. Galileo surely would have rejected this appraisal of his discovery of mountains on the moon, satellites of Jupiter, phases of Venus, and the laws wherewith he launched his "new science" of motion. For he, as we now know, made skillful use of demonstrative techniques to achieve his results, operating within the context of Aristotle's *Posterior Analytics* to overthrow the "old science" of the Schools.[2] Newton too was Aristotelian in his

2. See our *Galileo's Logic of Discovery and Proof. The Background, Content, and Use of His Appropriated Treatises on Aristotle's* Posterior Analytics. Dordrecht-Boston-London: Kluwer Academic Publishers, 1992; also Sec. 9.2 below. This is not to say that Galileo was an Aristotelian pure and simple, for he rejected many of Aris-

methodology, for he likewise used the Peripatetic methods of resolution and composition to discover "true causes" that were to put optics and mechanics on new epistemic foundations.[3]

With the modern scene in such turmoil we here suggest a return to a happier time when the philosophy of science was intimately joined with a philosophy of nature, as in Galileo's thought and explicitly in the title of Newton's *Principia*.[4] As the positivist program has shown, formal logic alone is powerless to supply an epistemology adequate to the needs of twentieth-century science. What is needed is a content logic such as that provided in Aristotle's *Posterior Analytics*, the key to *epistēmē* in its many applications throughout his works. But without the concept of nature, and the associated concepts of cause, substance, and power, the techniques of the *Analytics* cannot be made to work in the natural sciences. All of these concepts have to be reformulated and defined in terms intelligible to a modern reader. That is the point of the modeling techniques already mentioned and of their being highlighted in the title of the work, "The Modeling of Nature." Models and analogies are thus the principal means used herein to secure an intellectual grasp of the inner dimension of nature's operations.

In view of the book's aim to present an understanding of modern science that is explicitly based on the concept of nature, we offer it with the subtitle "Philosophy of Science and Philosophy of Nature in Synthesis." The coupling of the philosophies is meant to suggest that a renewed philosophy of science needs be grounded in a philosophy of nature, not in logic alone, even less in language and social studies. On this account the work is divided into two parts of about equal length, each devoted to a

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totle's teachings in natural philosophy; yet in matters of logic he was able to claim, only sixteen months before his death, that he had been a Peripatetic all his life (ibid., xv).

3. With his new theory of light and colors, wherein he showed that white light is composed of colored rays each of which has a different "degree of refrangibility," and with his theory of universal gravitation, which laid the basis for his celestial mechanics. Although Newton himself disclaimed knowledge of the nature of light or of the cause of gravity, he nonetheless held that enough could be known about light and gravity to provide scientific knowledge of them through the effects they produce. The claim here, as in the previous note, is quite modest: not that Newton was a Peripatetic, but that he was Aristotelian in some aspects of his methodology. Zev Bechler makes a similar but stronger claim about Newton, which he also extends to Galileo, in his *Newton's Physics and the Conceptual Structure of the Scientific Revolution*, Dordrecht-Boston-London: Kluwer Academic Publishers, 1991, 105–171.

4. As is well known, Galileo invoked nature as the basic cause of falling motion, and the full title of Newton's work is *Philosophiae naturalis principia mathematica* (The Mathematical Principles of Natural Philosophy).

philosophy. Philosophy of science is the major objective, but since nature itself is so poorly understood in the present day, we begin with the philosophy of nature in the first part and then, on the basis it provides, we proceed to the philosophy of science in the second.

Nature thus provides the focal point for Part One. In it no detailed knowledge of philosophy is presumed on the part of the reader. Instead, the main prerequisite is a general observational knowledge of the world of nature, plus the type of acquaintance one might have of the physical and natural sciences upon completion of high school. Reliance is placed on the reader's grasp of scientific knowledge simply from exposure to television and the popular press, where electronic enhancement of visual images and the use of computer graphics daily provide views of nature that were unavailable to, and unthought of, by previous generations.The order of exposition is that of the *corpus aristotelicum*, which treats first of nature in general, as explained in the *Physics* (Chap. 1), and then in particular, that is, as it is studied in the special natural sciences, where the general concept is instantiated with the major types. Thus in successive chapters epistemic models are provided of inorganic natures (Chap. 2), plant natures and animal natures (Chap. 3), and human nature (Chap. 5). The transition between the last two is facilitated by an intermediate chapter (Chap. 4), entitled "The Modeling of Mind." This introduces the reader to cognitive science and explains its strengths and limitations, covering in the process materials taught in traditional courses on logic, epistemology, and psychology. The fifth chapter then takes up human nature in detail, exploring additional aspects of psychology, particularly as related to ethics, and thus supplying fuller insight into the human soul and its functioning. By the completion of all five chapters, therefore, much more than a philosophy of nature will have been covered. The major philosophical disciplines that serve as a prelude to metaphysics are touched on, and with them one could have sufficient background to start on that difficult subject.

Aristotle provides the inspiration throughout this exposition, and one of its aims is clearly to disabuse those who write him off as hopelessly irrelevant to modern science, as though his view of nature had been repudiated by Galileo and Newton.[5] Yet the concern here is not with his Greek text and the state of natural science in the fourth century B.C. Rather what is proposed is a progressive Aristotelianism—following in

5. Both Galileo and Newton had a good grasp of the Aristotelian concept, and it is always in the background of their writing, though they preferred to focus on a mathematical treatment of natural phenomena rather than on nature itself.

the path of the many Greek, medieval, and Renaissance commentators who adopted Aristotelian principles while taking account of facts or sources of information that were not known at the time of their formulation. The ideal is that perhaps best set by Thomas Aquinas and his teacher Albertus Magnus, neither of whom was a slavish follower of Aristotle (as was the famous Arab commentator Averroes), but instead used the analytical techniques of their mentor to develop sciences completely unknown to the Greeks. Paradoxically, the ideal is also suggested by Galileo, who disagreed with many teachings proposed by the Aristotelians of his day, but who nevertheless was well acquainted with the methodology of the *Posterior Analytics*. Indeed, so well equipped was he that he could maintain that were Aristotle then alive and had access to the new empirical evidence he himself had made available, the philosopher would have sided with him rather than with his proclaimed disciples. Much more, of course, is here assimilated within an Aristotelian synthesis than could have been known to either Albertus, Aquinas, or Galileo, including information that has become available only in the late twentieth century. To aid the reader in situating in their proper time and place the various discoveries deemed important in this enterprise, footnotes have been inserted throughout the chapters to indicate when and by whom the relevant advances were first made.[6]

Part Two of the volume turns, not to metaphysics, but to the second philosophy in our subtitle, the philosophy of science, many of whose practitioners deny the possibility of metaphysics in its traditional understanding. The purpose of this part is twofold: to provide an epistemic justification of the insights provided in the first part; and, in the process, to delve into aspects of logic and epistemology that are treated more by philosophers of science than by natural philosophers. It begins with an overview of the philosophy of science movement as this has developed in the twentieth century, mainly in an Anglo-American setting, pointing out how it relates only tangentially to the study of nature (Chap. 6). Following this an analysis is given of probable reasoning as it has become canonical for philosophers of science in the U.S., showing its similarities with dialectical or topical reasoning in the Aristotelian tradition (Chap. 7). The main contribution then comes in the chapter entitled "The Epistemic Dimension of Science," where the case is presented for going beyond probable reasoning to restore the notion of *epistēmē* and,

6. In this project we have drawn heavily on Alexander Hellemans and Bryan Bunch, *Timetables of Science. A Chronology of the Most Important People and Events in the History of Science*. New York: Simon and Shuster, 1988.

through its use, to seeing some science, at least, as providing true and certain knowledge (Chap. 8). By way of application, eight conceptual histories are then considered, ranging from medieval to recent science, and detailing how demonstrations were actually arrived at in different fields of science (Chap. 9). The concluding chapter takes up various controversial aspects of these demonstrations and explains how disputes were finally resolved, thus supporting the epistemic thesis advanced in the previous two chapters (Chap. 10). Implicit in this discussion is a philosophy of science that is based on knowledge of nature rather than on formal logic and that harvests the fruit of science's history as this serves to clarify its philosophy. Thus it is able to bypass the technicalities that burden the literature of the philosophy of science movement and so bring the discipline closer to the common-sense realism by which scientists actually live and operate.

The model that provides the insight into nature on which the volume is based, the "life-powers" model elaborated in Chapter 5, was first sketched by the author in Newman Lectures at the Massachusetts Institute of Technology in 1961. The extension of that model to the human sciences, and then from human nature to the whole of nature, was not undertaken until 1984, when he was a fellow at the Woodrow Wilson International Center for Scholars, Washington, D.C. Fuller details have been worked out more recently, with added stimulus deriving from his studies of Galileo's early notebooks and their sources.[7] But the long-term motivation has come from over forty years of teaching both the philosophy of nature and the philosophy of science, graduate as well as undergraduate. The cross-fertilization of ideas this experience produced, and the appreciation and enthusiasm it awakened in students over the years, is his incentive for wishing to share with a wider audience the view of nature, and of the natural and human sciences, presented in these pages.

Many debts have obviously been incurred during the preparation of a

7. Apart from the volume cited in note 2 above, the main results of that study are presented in the author's following works: *Galileo's Early Notebooks: The Physical Questions*, Notre Dame: The University of Notre Dame Press, 1977; *Prelude to Galileo: Essays on Medieval and Sixteenth-Century Sources of Galileo's Thought*. Dordrecht-Boston: D. Reidel Publishing Co., 1981; *Galileo and His Sources: The Heritage of the Collegio Romano in Galileo's Science*, Princeton: Princeton University Press, 1984; *Galileo, the Jesuits, and the Medieval Aristotle*, Hampshire (UK): Variorum Publishing, 1991; and *Galileo's Logical Treatises: A Translation, with Notes and Commentary, of His Appropriated Questions on Aristotle's* Posterior Analytics, Dordrecht-Boston: Kluwer Academic Publishers, 1992.

work of this scope. Suffice it to mention only my two colleagues in the Dominican Order who laid the groundwork many years ago: Benedict M. Ashley, for his early guidance of the Albertus Magnus Lyceum, whose seminal work *Science in Synthesis* of 1953 laid out a plan that is now perhaps more fully realized[8]; and the late James A. Weisheipl, whose devotion to historical studies inspired me to extend his research in medieval science into the early modern period. I wish to thank also the readers of the manuscript, Robert Sokolowski, Rom Harré, and Maurice Finocchiaro, for helpful comments that saved me from a number of errors and otherwise assured me of the viability of this Aristotelian approach to the conceptual foundations of modern science.

William A. Wallace

8. The full title reads *Science in Synthesis: A Dialectical Approach to the Integration of the Physical and Natural Sciences*, ed. William H. Kane, Benedict M. Ashley, John D. Corcoran, and Raymond J. Nogar. Report of the Summer Session, July 1952, of the Albertus Magnus Lyceum for Natural Science, River Forest, Ill.: The Aquinas Library, 1953.

Illustration Credits

The illustrations in this volume are photoreproduced from pen and ink drawings prepared by the author. The majority are original compositions, but a number are drawn from pre-existing materials, as follows:

Figs. 2.1 through 2.3 are based on drawings in *Particles: An Introduction to Particle Physics*, by Michael Chester, diagrams by Erich Ingraham, New York: Macmillan Publishing Co., 1978, pp. 42 and 75.

Figs. 3.2 through 3.4 are adapted from drawings in *In Search of the Double Helix: Quantum Physics and Life*, by John Gribbin, New York: McGraw-Hill, 1985, pp. 144, 145, and 242.

Fig. 4.1 is a simplified version of diagrams in "An Artificial Insect," by H. D. Beer, H. J. Chiel, and L. S. Stirling, *American Scientist* 79 (1991), pp. 445 and 447.

Figs. 9.1 through 9.3 are sketches of drawings in manuscripts of *De iride et radialibus impressionibus* of Theodoric of Freiberg (c. 1310); cf. Joseph Würschmidt, ed., "Dietrich von Freiberg, Über den Regenbogen und die durch strahlen erzeugten Eindrücke," *Beiträge zur Geschichte der Philosophie und Theologie*, 12.5–6 (1914), pp. 50, 76, 78, and 135, and Maria Rita Pagnoni-Sturlese and Loris Sturlese, eds., *Dietrich von Freiberg, Opera omnia*, vol. 4, Hamburg: Felix Meiner Verlag, 1985, Figs. 6, 7, 9, 11, and 23, corresponding to pp. 135, 136, 158, 160, and 208 of the text.

Figs. 9.4 through 9.6 are based on drawings in Galileo Galilei, MS Gal. 72, Florence: Biblioteca Nazionale Centrale: Fig. 9.4 from fol. 114v, Fig. 9.5 from fol. 81r, Fig. 9.6a from fol. 175v, and Fig 9.6b from fol. 116v; cf. David K. Hill, "Dissecting Trajectories," *Isis* 79 (1988), pp. 658–659; idem, pp. 647–648; Ronald Naylor, "Galileo's Theory of Projectile Motion," *Isis* 71 (1980), p. 558; and Hill, ibid., *Isis* 79 (1988), pp. 663 and 665.

Fig. 9.7 is sketched from a diagram in the *Discourse on Method, Optics, Geometry, and Meteorology* by René Descartes, first published in 1637; cf. *The Science of René Descartes* by J. F. Scott, London: Taylor and Francis, Ltd., 1952, p. 75.

Figs. 9.8 and 9.9 are simplified versions of Sir Isaac Newton's diagrams in the *Philosophical Transactions* of 1671–1672; cf. *A Historical Introduction to the Philosophy of Science* by John Losee, Oxford U.P., 1972, pp. 82–83.

Part I. Philosophy of Nature

1 Nature: The Inner Dimension

Although it is easy to form a general idea of nature and the natural, it is difficult to define nature precisely and to differentiate things and processes that are natural from those that are not. A first approach to such a definition is to conceive the world of nature as what is experienced when a person goes into a primeval forest or gazes out on a starry night into the depths of space. The natural in such experiences is perceived as what is free from human intervention and artifice, what comes into being and runs its course without benefit of man's assistance or his contaminating influence. In this sense, the world of nature may be distinguished from the world of art and artifact: the latter is man's creation, whereas the former exists and acts independently of man, although it is available for his observation and, in some cases, for his manipulation and use.

Another sense of the natural differentiates it not from the artificial but from the forced or the violent, what is done from without or by coercion instead of coming from within the subject being studied. In this way of speaking, things have natures that are the sources of the activities they originate and so are peculiarly their own.[1] In a mechanically determined universe, all motions might appear to be imposed on objects externally, the way a person might be dragged from his home and taken elsewhere

1. This is the meaning given the term nature (*phusis, natura*) by Aristotle in his *Physics* (192b21–23): "a principle and cause of being moved or of rest in the thing to which it belongs primarily and in virtue of that thing, but not accidentally." Galileo captured this sense in his early notebooks when he wrote: "Nature is a principle of motion; from this it is apparent that a different motion indicates a different nature." Again: "For the naturalness of a motion an intrinsic cause is required, not an extrinsic one." Similarly, Newton wrote in his Trinity notebook: "Natural things are thus whatever comes to be in the order of nature, or within any of which there is a principle of motion and rest."

against his will. "Doing what comes naturally," on the other hand, designates a type of activity that originates within the agent, more or less spontaneously, and is not the exclusive resultant of forces imposed on the object from without.

Combining the two senses, we may characterize the world of nature as what is capable of coming into existence apart from human influence and as made up of things that have within themselves natures or internal sources of their distinctive activities. Nature is thus populated by plants and animals of various kinds, by chemical elements and compounds, by hosts of elementary particles, by galaxies, stars, and planets, all of which come into being and pass away and yet enjoy periods of relative stablility during which they respond to, or interact with, objects around them. Some natures are animate whereas others are inanimate, yet all are knowable through observable properties and behavioral characteristics. To say of something that it is sulphur, or a geranium, or a horse, is to specify its nature; this we learn not merely from its appearance but from the way it acts and reacts in a variety of circumstances. Thus understood, there is something more enduring about natures than there is about the individuals that instantiate them. A plant may die, and when it does it ceases to be, say, a geranium, but its perishing does not entail that the nature of geranium ceases also. Other plants may continue to exist of which it is true to say "This is a geranium," and thus the nature has a less transient character than the individuals of which it is predicated.

Again, to say of a horse that it is a large, solid-hoofed, herbivorous mammal is to describe, and indeed to define, its nature. The definition sets it apart from things that are not mammals, and among mammals it further differentiates the horse from small creatures, carnivores, and those without solid hoofs. This in fact becomes the meaning of the term "horse." Furthermore, the grasp of such meaning is the work of the intellect, not merely the work of the senses. Natures are a shorthand way of indicating the intelligible aspects of things in terms of which they can be understood and defined. Thus the concept of nature is not exclusively an empirical concept, if by empirical one means whatever can be measured or photographed or otherwise presented directly to the senses. It is transempirical, for although it takes its origin from sense experience it still requires going beyond the world of sense for its proper comprehension.

To refer to the nature of a thing is therefore to designate an inner dimension that makes the thing be what it is, serves to differentiate it from other things, and at the same time accounts for its distinctive activities and responses. This inner dimension is not transparent to the intellect, for we usually do not achieve distinct and comprehensive knowledge of a nature the first time we encounter it in experience. Rather we grasp it in a general and indeterminate way that is open to progressive development and refinement on the basis of additional information. A veteran horse trainer or a veterinarian obviously knows more about the nature of a horse than does a youth with limited experience of horses. Yet even the child who is able to say "That is a horse" grasps the same nature as does the expert, even while doing so in a vaguer and less distinct way.

When approached in this manner, nature loses some of the mysterious and occult character sometimes associated with terms such as essence and quiddity. To seek the essence of a horse is in effect to define it or determine its nature. To ask for its quiddity (from the Latin *quidditas*) is similarly to ask what it is, and this is nothing more than to inquire into its nature. There is nothing spooky or metaphysical about such an inquiry. Rather it is a natural way of questioning for a human being who wishes to gain understanding of the world of nature and of the many natures of which it is constituted.

1.1 The Causal Model

The fact that a nature is only progressively disclosed in experience, and perhaps is never exhaustively understood, makes it especially amenable to study through modeling techniques. Now there are many meanings of the term "model," and models are used in scientific investigation in a number of ways.[2] For purposes here, a model will be taken to be an analogue or analogy that assists or promotes the gradual understanding of something not readily grasped in sense experience. Knowledge growth in humans is far from being a simple accumulation; rather it is a complex process whereby we perceive and learn from things around us by noting their similarities and differences. When we encounter something new, we attempt to understand it by conceiving it after the fashion of what is already familiar to us. We thus use the things we know, or at least think we know, to advance into the realm of the unknown. Models or analogies are helpful in this process, and they can be particularly helpful for grasping the concept of nature.

To elaborate further, a model as used in discovery and clarification,

2. One of the best general treatments of models and their use in the sciences is that of Rom Harré, *The Principles of Scientific Thinking*, Chicago: The University of Chicago Press, 1970, Chap. 2. Additional details are provided in the sections that follow, especially Secs. 1.8–9, 2.2, 2.9, 3.2–4, 3.6, 4.4, and 5.1.

which we shall henceforth refer to as an epistemic model, has two referents that can serve to explain its function. The first is something more known, from which the model is taken, and the other is something less known, to which the model is applied. The more known factor may be referred to as the source or origin of the model, and the less known factor may be called its application. Thus the model is taken from one thing, its origin, and is used to understand another, its application.

The first model we shall introduce is a simple explanatory model known as the causal model. This takes its origin from the world of artifacts and is readily applied to the world of nature. As an explanatory model it identifies four factors that are usually called causes, though not all in the same sense, since each functions in a distinctive way when providing a causal explanation. By reflecting on the ways in which causes are used in understanding artifacts, however, we can discern analogous ways in which they may be employed to gain an understanding of nature. It is in this fashion that nature may be modeled from artifacts, for things we make are quite intelligible to us and so can cast light on natures that are less obvious to our intellects.

The four factors involved in the causal model are usually identified as matter, form, agent, and end. Sometimes the word "cause" is explicitly associated with each of these factors, and then matter becomes *material* cause, form *formal* cause, agent *efficient* cause, and end *final* cause. Whether "cause" is added explicitly or not, each of the factors explains why the thing to which it is applied came to be and is the way it is. Thus they are principles for understanding entities in the order of becoming and in the order of being as well.

When analyzing a chair on the basis of this model, one has no difficulty identifying the first two factors, matter and form. The matter is the stuff or material out of which the chair is made and which remains in it—for example, wood, or, to be more precise, cherry or oak. The form is the shape or design imposed on the wood during the chair's making. Both of these factors are internal to the chair, that is, they are within it and serve to explain its composition in the order of being, and so we call them internal causes. The remaining two factors are external to it and are mainly of help in explaining how and why the chair came to be. The agent is the carpenter or craftsman who fashioned it from raw materials, and the end is the goal or objective he had in mind when so doing, say, to construct a presentable piece of furniture on which one can sit comfortably. They are principles more in the order of becoming than in the order of being, though once made the chair retains a relationship to its maker and also embodies the goal he had in mind when making it.

If one applies this causal model to a clarification of the meaning of nature—as, for example, what is meant by the nature of sulphur—one might think that only two of the factors mentioned are immediately relevant. If nature is the source of distinctive activities that originate within a thing and are not imposed on it from without, only internal factors seem relevant. These are sulphur's matter, or the stuff out of which it is made, and its form, the structure or design assumed by that matter when sulphur comes into being. This is not to say that no agents or efficient causes are operative in the order of nature, or that no goals or ends are intended and achieved through nature's operations. But with regard to sulphur it is difficult to identify the agent that produced it or the end for which it was produced, and thus these external causes would seem not to be part of its nature.

1.2 Matter as Nature

If the matter or material cause of a natural entity is the stuff from which it is made and which remains in it, precisely what that stuff is invites clarification. Comparison with the artificial analogue will help show the difficulty here involved. If we were asked to identify the material out of which the chair is made, we would reply "wood," or perhaps "cherry" or "oak." The substance used in making the chair remains in it and is observable throughout the incidental changes of position, temperature, and treatment it might undergo. The material that underlies chair is open to inspection, and indeed can often be identified as having a nature in its own right, say, that of oak. Not so simple is the identification of the material out of which sulphur, or an oak tree, or a horse might be made. If it is to satisfy the requirements of a material cause as seen in the artifact, it must be some underlying stuff out of which the natural entity is made and that continues to remain in it. That there is such a stuff seems obvious on the face of it, but precisely what it is poses a problem.

It is at this point that the natural philosopher can be of help in finding a solution. From the speculations of the ancient Ionians to the latest researches of high-energy physics, philosophers have attempted to identify elements in nature that serve to explain the composition of natural substances. Usually the investigative technique has consisted in studying the transformations such substances undergo as they are either generated out of preexistent materials or broken down into them. The earliest proposals were for water or air to be the primordial element from which natural entities are formed. To these were later added fire and earth, and then all four were grouped together in what is called the four-element theory. Celestial bodies were then thought to be composed of a fifth element, a quintessence, otherwise known as aether. Such an explanatory scheme was universally adopted until the eighteenth century, when the chemical revolution brought in hydrogen, oxygen, nitrogen, carbon, and other substances as better candidates for elemental status. And as long as scientists were content to regard these material constituents as minute enduring atoms, too small to be seen but incapable of being broken down in further parts, an answer seemed at hand for the question being asked. One could say that artifacts are made from natural substances, and that the latter are formed from chemical elements such as those listed in the periodic table. These appeared to be the stuff nature used in making them.

Such an answer sufficed for a considerable time, and even in the present day might be accepted as the deepest one can penetrate when investigating the material cause of natural entities. Yet its shortcoming becomes apparent as soon as we inquire about the nature of sulphur or other chemical element. What is the stuff of which the elements themselves are made? Then, if we continue the search for more and more elemental constituents, and frame answers in terms of electrons and protons and neutrons, etc., the question continues to recur. The ultimate matter nature uses to form such particles, the stuff out of which they come into being and pass away, remains mysterious and elusive.

More will be said about the material substrate of natural substances in later chapters, as this is of key importance for understanding nature as an inner source of characteristic properties and activities. For now it may suffice to note that Aristotle spoke of the ultimate material component of natural entities as *hulē prōtē*, a Greek expression meaning protomatter (PM) or first matter.[3] He thought of it as a type of conservation principle that persists through all natural changes in the universe. Surprisingly, scientists have come to develop a similar conception in recent years. No longer do they attempt to identify one final substance, a single super-quark, for example, that is the ultimate building block of the universe. Instead their emphasis is on delineating factors that are conserved in all the transformations that take place in the world of nature. Such conservation principles have been known and investigated for some time. They have been successively formulated as the conservation of

3. In the second book of the *Physics*, 193a28–29, where he describes it as "the immediate material substratum of things which have in themselves a principle of motion or change." Earlier he had identified it in the first book as the *hypokeimenē phusis* or the "substratum of nature" or simply as *hulē* or "matter" (191a7–11).

matter, energy, mass, and finally, after Einstein's discovery of mass-energy equivalence ($E = mc^2$), mass-energy.[4] Perhaps the last named, mass-energy, comes the closest to conveying the Aristotelian idea of protomatter as the basic stuff of the universe. Whatever quarks may be, or leptons and hadrons in their various forms, it seems generally agreed that all are manifestations of mass-energy, the ultimate matrix to which science seems to have come in identifying the material cause of the universe.[5]

A surprising implication of this line of reasoning is that matter, as a basic constituent of all natural entities, is no longer seen as the passive and inert component it was previously thought to be. Rather it is a powerful and potential principle that lies at the base of the most cataclysmic upheavals taking place on our planet, to say nothing of those in the remote depths of space. And not only does nature explore those potentialities, but man, through his ingenuity, has succeeded in triggering some of them himself.[6] This achievement, the most breathtaking of the twentieth century, is also one that gives pause to anyone interested in studying man's nature and evaluating his place in the universe as a whole.

1.3 Form as Nature

Returning to the causal model based on our artifact, the chair, we note that its form is intimately related to its matter, in the sense that the form is the shape or figure the matter assumes during the chair's manufacture and becomes, as it were, part of its being. Moreover, although the wood, say, oak, was not always formed as a chair, as long as it was identifiable as oak it was always seen under one form or another, and from this point of view the two, matter and form, seem quite inseparable. One might think from this correlative status that both are equally unintelligible, that, just as there is something mysterious about the basic matter of the universe, so the forms it assumes or to which it is united are difficult to

4. First announced in a paper on special relativity submitted by Einstein for publication in September of 1905.

5. In his *Physics and Philosophy* (New York 1958) Werner Heisenberg writes: "The matter of Aristotle is certainly not a specific matter like water or air, nor is it simply empty space; it is a kind of indefinite corporeal substratum, embodying the possibility of passing over into actuality by means of the form" (148). Later he suggests that "the matter of Aristotle, which is mere 'potentia,' should be compared to our concept of energy" (160).

6. That is, by the experimental explosion of a nuclear device in July of 1945, and then by the explosion of two atomic bombs in August of the same year.

grasp as well. This is not exactly the case, for though matter is to a large degree refractory to the human mind, form is surprisingly intelligible. It provides a window through which the world of nature is seen and through which many of the natures that inhabit it can be readily understood.

That this is true may be seen from the ways we speak about the natural objects, and not merely the artifacts, that fall under common observation. We are able to identify most of the animals, plants, and minerals with which we come in contact, and we are also able to classify them in ways that show our awareness of the differences among them. Moreover, though many of these objects have a multiplicity of parts and are far from homogeneous in structure, we grasp them in a unitary way and ascribe one nature to them. It is this formality, or form, that we name and define as we become acquainted with natural kinds, with substances of different types found in our environment.

How to describe or characterize this natural form in a way that differentiates it from the shape or configuration of an artifact presents a more difficult problem. Obviously the outline or silhouette of a cow or a giraffe is a help in identifying it and is closely associated with its nature. In this respect it resembles the form of an artifact. But the shapes of organisms vary over a wide range, in one individual throughout time and indeed from one individual to another, even though the natures underlying the shapes may be the same. Similar statements could be made about most of the quantitative and qualitative attributes that are found in natural substances. All of these can be understood as so many forms that make the particular substance intelligible and enable us to distinguish it from others in number and kind. So as to differentiate such forms from the form that gives unity to a nature, philosophers speak of the latter as a substantial or natural form (NF), a form that underlies its attributes and makes it a substance in its own right. Incidental attributes or properties they then refer to as accidental forms (AF's), intending by this forms that are conjoined to the nature either as properties or as adventitious modifications that may vary in degree or in presence and absence without altering the basic character of the substance.

It is this natural or substantial form that is apprehended when one grasps the nature of an entity and attempts to define it. Like the nature, this formal component is not an empirical concept: it is not given immediately in sense experience, though it is derivable from such experience. It has more the features of a universal than of a particular representation. That is why the defining notes or attributes of lead and copper, of rose bushes and oak trees, of mosquitoes and kangaroos, apply not only to this or that lead, copper, rose bush, etc., but to each and every instance of them. Were this not so, it would be impossible to have universal knowledge of the world of nature, and a fortiori any science of nature. We would be limited to cataloguing individual after individual, without ever being able to discern natural kinds, that is, the substantial features they have in common, notwithstanding the many ways they may differ numerically within a species or class.

The simplicity and unity of the natural form should not obscure the many attributes and activities that derive from it and of which it is the inner source. To speak of a horse as a mammal, for example, immediately signifies that it belongs among higher vertebrates that nourish their young with milk secreted from glands of a special type. This entails a complex organism with structures and organs that function in interrelated ways to assure the well-being of the whole. More will be said later about the ways in which activities originate within such natural agents, but for now it need only be mentioned that the unifying form, no less than the underlying matter, is the internal source from which all such activities ultimately spring. Behaviors, actions, and reactions are natural for a substance precisely to the extent that they proceed from within it, and thus from its matter and form as its basic intrinsic constituents.

Much the same point can be made by contrasting the natural or unifying form with the artificial form of chair in our causal analogue. The shape or design of a chair is basically a matter of geometry and is no more the source of activity than is the figure of triangle when this is abstractly conceived and not embodied in wood or plastic. A wooden triangle can fall or be broken, whereas an abstract triangle cannot. Similarly a chair can undergo change: it can be scratched or gouged, thrown down stairs, burned in a fire. But it cannot be so changed *precisely as* chair, but rather as something made of oak or other material. Indeed, it is the nature of the substance out of which it is made that determines what can be done with it and how it reacts to forces impressed upon it. It is in this sense that the natural form is the inner source of activities and reactivities, whereas the artificial form (or any other accidental form, for that matter) is not.[7]

What has been observed thus far is applicable to natures found in

7. It should be noted, however, that an accidental form can assist a motion or activity despite the fact that it is not a natural form. Thus the round shape of a wooden wheel facilitates the wheel's movement, whereas its being made of wood is what makes it moveable. This is the point of Aristotle's adding the expression "but not accidentally" to his definition of nature cited in n. 1.

common experience and readily apprehended by the senses. Special problems are posed by entities in the microcosm and those in the remote depths of space, which will be addressed in their proper place. But here a methodological point needs to be made. The possibility of a science of nature, or of a science based on natures, is jeopardized if one begins straightaway with atoms or subatomic particles as though these were immediately given, and then attempts to construct the entire universe out of them. It is not apparent that electrons and neutrinos even exist, let alone that they have natures in terms of which they can be understood. This is not to prejudice the case against causal explanations that make use of elementary particles, or against modeling techniques that would investigate their characteristics as well as those of quasars, pulsars, and other stellar objects. The point is rather that entities remote from man's experience, which require elaborate instrumentation and theoretical construction for their very discussion, are *prima facie* lacking in the intelligibility that enables one to grasp a nature, and thus are poor candidates with which to *begin* a study of the natural world.

1.4 Nature as Agent

Moving now to the third explanatory factor in our causal model, the agent or efficient cause, we may inquire what analogue there is in nature that corresponds to the maker of the chair in the case of the artifact. Here it is important to stress that the making of the chair is an activity of the maker, and as such is readily correlated with a capability that preexists in the maker and is the proximate cause of his activity. A general principle is latent in the example: operations and activities, and reactivities as well, proceed from abilities and potentials that are lodged in the natures of agents and so can serve to explain the ways in which they act and react with neighboring objects. Natural forms are the inner source of these activities, but such forms are equipped with powers that can be activated and so enable substances to act on, and interact with, things external to them is distinctive ways.[8] It is the ability of one substance to act on another that explains why it is possible to identify agents and reagents in the order of nature.

Now man is a natural organism that possesses many powers and capabilities, and on this account he can serve as a paradigm for the inves-

8. The Greek term for power or capability is *dunamis*, the source of our word dynamic. Aristotle defines it in his *Categories*, 9a14–28.

tigation of agencies in nature. It is natural for man to think and to will, to speak and to write, even to dream, but these distinctively human activities—while providing an insight into his nature—are not the focus of attention at this point. Being perfective of man's mind rather than his body, they are not particularly helpful for seeing how his body can act on other bodies and thus serve as an efficient cause. A carpenter's making of a chair, on the other hand, illustrates a natural agent at work on another body, forming its material into a useful artifact. This primitive example of *homo faber* could be extended indefinitely as one ranges through all the constructive, mechanical, and industrial arts, the feats of engineering, the products of technology in our century. Man is a powerful agent who acts, directly and indirectly, on the substances around him, appropriating them and transforming them in countless ways to suit his needs and desires.

Similar instances can be adduced in the animal and plant kingdoms. Beavers build dams, birds their nests, and spiders their webs, and in all these natural activities they use or affect objects with other natures to the benefit of themselves and their species. Animals give birth to young and plants bear seeds, thus serving as agents for bringing new organisms into the world. And through the balance of nature, fauna and flora convert chemical substances and direct solar energies to provide food and nutriment for a wide range of species. All living organisms, in their life processes, are so many agents that interact with their environment and produce changes in other things in the course of their development.

At the level of the nonliving, on the other hand, agencies are not so easy to identify and on this account have been poorly understood for centuries. Again the chemical revolution has led to remarkable insights into the ways elements interact with each other to form compounds, how minerals are formed in the bowels of the earth. Chemicals have affinities, and given the proper circumstances these manifest themselves as abilities to enter into combination with other substances, thus affecting them and in many instances giving rise to new natures. Although such reactions can be studied and realized in the laboratory, they are natural processes that are initiated by the agents and reagents that enter into them. Strictly speaking, there are no chemical artifacts: all new substances are the work and product of nature, bringing to actualization the potentials latent in the materials from which they are formed, under the influence of the various catalysts and initiating conditions that help bring them about.

Physical agents are frequently seen as exerting forces on surrounding objects and thus causing motions and changes of state in them. In this view, a force is itself an instance of an efficient or agent cause. Indeed, the use of the force concept in the physical sciences illustrates how pervasive agency or action is in the realm of the inorganic. But it should be noted that a forced motion requires more than an intrinsic agent for it to occur; it also demands a nature within the object that is being acted upon. Only because an oak chair is made of oak can it be shaped with a tool or carried from place to place by a mover with sufficient strength to move it. The reactivity of the oak to the tool or to the mover may well be conceptualized as a resistive force exerted from within the oak, but this arises only because an external agent has acted on it and caused it to react as it does in accordance with its nature.

Physicists link forces with energies and fields, and these provide a further source of information about natural agents. Studies of the structure of matter using high-energy techniques yield four major forces that are believed to underlie all of nature's transformations. These will be discussed in the next chapter. Whether or not such forces will ever be accounted for by a unified field theory—and so seen as instances of one basic force of nature—each provides an example of the ways in which the material components of the universe act on each other and produce the phenomena that are observable within it.

Just as there are problems concerning matter and form when these are viewed in a most fundamental way, so there are difficulties in understanding natural agency in its most radical form. Gravitational force is a good case in point. For centuries bodies were thought to be heavy because of *gravitas* or a force of gravity *(vis gravitatis)* inherent within them that caused them to seek their proper place in the universe. With the advent of Newtonian mechanics, gravity came to be conceived as an attraction whereby one body, say the earth, exerts a pull on another body, say the moon, and retains it in proper orbit.[9] Einstein's proposals in his general theory of relativity eliminated these Newtonian forces and replaced them by geodesics or paths through the regions of varying matter density that bodies follow in space-time.[10] More recent proposals associate all forces between objects with an interchange of particles or

9. Newton described what he meant by attraction in his *Mathematical Principles of Natural Philosophy*, the first edition of which appeared in 1687. He attempted to formulate it as a purely mathematical notion without assigning it any "physical causes or seats."

10. Einstein completed the general theory of relativity late in November of 1915; it was published in the *Annalen der Physik* in 1916.

energies between them. With each advance, the agency involved in explaining gravity seems to have moved farther away from the gravitating body. Although such a body unerringly pursues the path of its fall, one who now attempts to calculate that path must take into account objects most distant from it, perhaps to the very bounds of the universe. Yet all seem agreed that there is something *within* the body, say its mass or mass-energy, that is a key explanatory factor behind its fall. In this sense, at least, they see the fall itself as one of the body's natural motions.

An equally perplexing difficulty regarding external causes is associated with the theory of evolution. Chemists feel reasonably sure that they know how elements evolve into compounds of more and more complex structures, all the way to DNA with its replicating potentials. Physicists similarly are confident of their ability to explain how chemical elements originated and were then distributed throughout the universe in their present relative abundances. Biologists understand genetic and reproductive mechanisms and know how one pair of mice produce other mice, organisms the same in species and similar in family characteristics. Yet when one considers the entire chain of being, from the simplest particles to the most developed animals now living or preserved in the fossil record, one finds it difficult to identify the cosmic agents that might cause a particular species to come from another, or to evolve into yet another species possessing capabilities not found in its forebears. Getting more from less, or something from nothing, is an attractive prospect, but nothing is more puzzling than uncovering the agent causes that permit its occurring on a grand scale in the universe in which we live.

1.5 Nature as End

This brings us to the fourth and final factor in our causal analogue, the end or final cause. The Greek word for end is *telos*, source of the term "teleology," so with this type of cause we come to the thorny question of teleology in nature. Since the time of Aristotle it has been almost axiomatic that nature acts for an end.[11] If evolution is viewed as a natural process, does this also entail that it is a teleological process, one that is goal-directed, in the sense that higher and more developed species are not merely the result of chance but were somehow determined in advance? There is no easy answer to this question, but its very asking en-

11. Aristotle introduces the notion in chap. 3 of the second book of the *Physics*, where he defines end or final cause (194b31–195a2). He then applies it to nature and its activities in chap. 8 of that book.

ables one to reflect on ends or final causes and how these may be operative within the world of nature.

It can be helpful here to distinguish three different meanings of the word "end," not all of which are equally identifiable in natural processes. The first and simplest meaning is that of end in the sense of terminus, the point at which a process stops. In a journey from New York to Washington, the nation's capital is the end of the trip, the place where the traveler comes to rest. Similarly the natural fall of an object terminates when the heavy body either reaches the center of gravity to which it is tending or encounters some obstacle that impedes its motion and brings it to rest. A plant grows from a seedling to full maturity, at which point it stops growing; the same could be said of the developmental process of a flea or an elephant. Natures are stable kinds, that is, within a certain range they represent regions of stability in a world of flux. In our experience fleas do not grow and grow indefinitely, say, until they reach the size of elephants, nor are elephants found as small as fleas. Growth processes terminate; to the extent that these are natural processes, the states at which they terminate are ends reached by nature and so satisfy the first meaning of final cause.

This same meaning applies also to the more fundamental processes that bring natural substances into being and are quite readily seen in the realm of the inorganic. Hydrogen and oxygen combine to form water, sodium and chlorine to form salt. In such reactions each of the reagents loses its own being and properties; new substances or natures emerge, and these have different, in most cases radically different, sets of properties. Chemists are interested in determining the factors that make such reactions go, but no less interesting is the question what makes them stop. Elements or isotopes with high atomic numbers break down radioactively, but again they do not do so in an unending and completely indeterminate way. At some stage the radioactive breakdown ceases, and this, as in the case of chemical combination, occurs when a stable nature has been reached. In the plant and animal world similar examples abound. Sperm and ovum unite to form a zygote, which divides and subdivides repeatedly, eventually to form a multicellular, stable organism of a given kind. Monsters occasionally occur, but with astounding regularity mosquitoes generate other mosquitoes, squirrels other squirrels, and so on. In this way nature is more than an inner source of change and activity; it is also a source of permanence and stability. When such stability terminates a natural process, whether inorganic or organic, it is the end of the process and as such its final cause.

A second meaning of end or goal adds to the idea of terminus the notion that it is somehow a perfection or good attained through the process. In some instances of natural change this meaning is easily verified, in others it is not. Clearly in cases of organic growth the end product represents a superior grade of being over the stage at which it began. It is also more perfect, in the etymological sense of *per-factum*, as that which is thoroughly made and possesses no *de-factum*, i.e., is lacking in nothing it should possess as a member of its species. In inorganic changes it is difficult to see in what sense a compound is better than an element, or an element of higher atomic number better than an element of a lower. Perhaps one should differentiate here between processes that are good for a particular nature, say, to conserve it in being, the way in which salt crystallizes and so preserves its identity, and those that are good for nature as a whole, the universe being made up of many different kinds. Elements are good in themselves, but compounds may better or more readily serve the needs of the organic world; plants and vegetables represent a higher stage of being than complex molecules, but less than that attained by the animals that eat them and incorporate them into their substance. If this seems true in the observable order of nature, it would be even more so in the evolutionary order, if such is indeed the work of nature. The successive production of higher and higher types undoubtedly represents some kind of progress, some greater good or perfection that is attained over time, presuming that the later types are not mere freaks or the result of chance occurrences.

The third meaning of end is more specialized still, for it adds to the notion of termination and perfection that of intention or aim. This serves to identify the type of final causality found in cognitive agents. Animals and humans are natural agents of this type: many of their activities are planned or intended in advance and so can be seen as end-directed from their beginning. A person building a house or a bird a nest must have in advance some notion of what is intended, for otherwise neither builder would know how to gather the materials. There seems to be a difference in the two cases, however, for the bird does its work by instinct and tends to make the nest in a form that is predetermined by its species, whereas man is not so limited and can generate the multiplicity of dwellings recorded in human history.

Much of the difficulty with teleology in nature arises from conceiving all final causality as intentional or cognitive and not sufficiently differentiating the cognitive from the terminative and the perfective. The medievals gave expression to such a mentality with the aphorism *opus* *naturae est opus intelligentiae*, the work of nature is the work of intelligence.[12] If by saying this one means that every natural agent consciously is aware of the goal at which it is aiming, there is little evidence that such could be the case throughout the entire order of nature. The word intelligence, however, can take on a variety of meanings, as is clear from the way one talks of artificial intelligence in the present day. Perhaps in the latter way of speaking one could say that the double helix is programmed to replicate in a certain way and so "knows" how to do it, or that an asteroid "knows" how to find its path through the solar system without performing the calculations we make to predict its path. In this sense, natural agents seem to foreknow what they aim to achieve and so implicitly substantiate the claim that nature acts for an end.

Such considerations open up the complexity and mystery of final causality in nature, analogous to those already uncovered in the investigation of other lines of causality. Matter and form are easy enough to grasp in a general way, and yet understanding ultimate matter and unifying form presents difficulties of considerable magnitude.[13] Natural agents are pervasive in the universe and are readily identifiable, but cosmic agents are largely hidden and so have managed to escape detection for centuries. Final causes exert their influence in terminative and perfective ways, yet they too give rise to serious problems. Is there an ultimate goal to which nature tends? Is there an intelligence behind its operations that organizes its matter and its agents so as to achieve that goal? More will be said about these questions in what follows; here their very statement illustrates the type of puzzle to which the notion of teleology in nature invariably gives rise.

12. The first Latin author to use the expression seems to have been Albert the Great. For a full discussion, see J. A. Weisheipl, "The Axiom 'Opus naturae est opus intelligentiae' and Its Origins," in *Albertus Magnus—Doctor Universalis 1280–1980*, ed. G. Meyer and A. Zimmermann, Mainz: Matthias-Grünewald-Verlag, 1980, 441–463.

13. René Descartes presents a good example of a philosopher who never was able to comprehend matter and form as ontological co-principles. It was inconceivable for him that there be any such thing as substantial principles since their status in being would evade precise mathematical determination. In his view matter must be an extended, actual thing, since "potency" is only a confused notion. And, if a form is substantial, it must be capable of subsisting by itself and hence must be a thing or complete substance. His insistence on "clear and distinct ideas" as a starting point effectively blocked for him access to the concepts of protomatter and natural form.

1.6 Necessity in Nature

Mention has already been made of freaks or monsters, by which is meant natural entities that are defective in some way and so do not reach the perfection proper to their species. Abnormalities are of course found among humans: these are the subject of continuing concern, particularly when suspected to be the result of man's interference with natural processes through the use of drugs or other artifice. Even apart from human influence, however, there is abundant evidence that "mistakes" occur in nature: runts turn up in many animal species, a zebra without stripes will occasionally be found in a herd of otherwise normal specimens, and malformed limbs and organs are possible in every kind of living organism.[14] Chemical reactions sometimes do not go, and crystals are not formed with the regularity one might expect. The occurrence of such exceptions to nature's course raises a question about the necessity of its operations and the degree of determinism one may expect to find in them. It may also explain why difficulty is experienced with the notion of nature's acting for an end, since from time to time nature falls short of the goals it seems to have intended to achieve.

To these problems, which relate to the way a particular nature is formed or developed, there are others that can be added when the universe is considered as a whole. Lightning strikes in a forest and brings down a towering redwood. Herbivorous mammals graze in fields and consume otherwise flourishing grasses and herbs. Large fish eat smaller fish, and throughout the entire animal kingdom carnivores prey on their victims. Slogans such as "nature red in tooth and claw" and "survival of the fittest" capture this side of the world of nature. Even though particular natures come into being and tend to develop in consistent ways, there is always the possibility of the accidental happening, the contingent or chance event that frustrates such tendencies and renders them ultimately fruitless. Whether the agents are cosmic or ecological, say, a meteorite crashing into the earth's surface or neighboring species preying on each other, the end result is the same. Nature's necessity is far from absolute, and one may even wonder whether it is more capricious than determinate in its mode of operation.

The issue of necessity and determinism is important from the viewpoint of the causal model here being employed to understand nature, for it bears directly on the possibility of ever attaining a strict science of na-

14. Aristotle of course was aware of monstrosities occurring in nature, and attributed them to failures in the order of final causality. See his *Physics*, II.8, 199b1–14.

ture. There is a tendency in the present day to equate causality with determinism, to think of a cause as operating mechanically and as being rigidly connected with its effect, making it indefectible in its causing. Coupled with this, scientific knowledge is thought to be necessary and universal, allowing for no exceptions, and thus to be attainable only where complete certitude is possible. Such views of science and causality, equating them in effect with absolute necessity and complete determinism, work against the understanding of nature being sought here. Indeed, the presence of contingency in nature need not preclude the possibility of a knowledge of natures that has universal validity, nor need the fact that some causes are impeded rule out causality as a basic principle of explanation.

If there is to be a science of nature, therefore, it seems important to differentiate such a science from those that claim absolute necessity and certitude in their results, such as mathematics and logic. A logician might be completely stymied, for example, in attempting to go from the observations that "This zebra is striped" and "That zebra is striped," and so on, to the universal statement "All zebras are striped." There is nothing in logic that of itself permits him to induce the universal from the particular, or otherwise to take into account the possibility of the albino zebra that turns up, admittedly rarely, white and unstriped. Yet chance and contingency are part and parcel of the natural scene. Both are the result, of course, of accidental causes. Chance events are far from being uncaused—lightning is very much the cause of the fall of the redwood, just as the robin causes the death of the worm and a metabolic deficiency causes the absence of pigmentation in the albino's skin. A natural scientist must know what to do with these adventitious causes and with the irregularities they introduce into his subject, for otherwise they will prevent him from developing his discipline in a systematic way.[15]

It is here that final causality, instead of being ruled out of the science of nature, offers a distinctive way through its difficulties. The necessity of nature is not absolute: rather it is a conditional or suppositional necessity, a *necessitas ex suppositione*. This type of necessity is best understood in relation to the end or final cause, and on this account is said to be "on the supposition of an end" (*ex suppositione finis*).[16] The care-

15. Galileo was extraordinary in his use of the notion of accidental causes (*causae per accidens*) to eliminate problems arising from friction and other impediments in his investigation of falling motion. For details, see our *Galileo's Logic of Discovery and Proof*, esp. chap. 6.

16. The Latin expression *ex suppositione* is simply a translation of the Greek *ex hypotheses* found in chap. 9 of the second book of Aristotle's *Physics* (200a14). As

ful observer of natural processes can detect a uniformity or regularity in them and in so doing become aware of the ends at which they normally terminate. Given the proper conditions, acorns develop into oak trees, a fact that can be verified through repeated observation and experiment. This fact obviously does not entail that every acorn will become an oak: some are gathered by squirrels, others wither away from lack of nutriment, and others seemingly on their way to becoming sturdy plants are cut down accidentally or deliberately. On this account one cannot say "If there is an acorn, there will necessarily be an oak tree." But the converse line of reasoning does have validity. On the supposition that nature is to produce an oak tree, that is, that such a tree is to terminate a natural process of development, an acorn is quite necessary to start the process. In fact, throughout the entire order of nature, *if* particular ends are to be achieved (and therefore on *their* supposition), determinate agents are required to act on specific matter to bring the appropriate natural form into being. The case here is quite similar to that in our artificial analogue. Given pieces of oak, there is no absolute necessity that they will assume the form of a chair. But on the supposition of an oak chair being made, then not only is the oak necessary but also the carpenter who has its idea beforehand and the necessary tools, and skill, to bring it into being. Similarly a suppositional necessity, based on the regularity of nature's operation, is sufficient to ground causal analysis and to reflect the type of determinateness that is to be expected in nature's otherwise contingent subject matter.

Reflection on this methodological procedure can shed light on a problem associated with evolutionary theory hinted at above. Mistakes and defects occur in artifacts no less than in nature: a chair may prove defective because the wood was worm-eaten and rotten or because its parts were improperly fastened together, and a monster might appear because of defective seed or an improper agency, say, radioactivity, affecting the developing organism. In the latter case a squirrel could produce a non-squirrel, and this for purely accidental reasons. Now if we are committed to the origin of species by evolution, and regard this as a natural process, then we must explain the converse case, that is, how squirrel comes from non-squirrel, and even can do so on a regular and law-like basis that also explains why oak can come from non-oak. For to say that squirrels come from non-squirrels by accident is to ascribe a fortu-

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for *ex suppositione finis*, the best exposition of this notion is to be found in Thomas Aquinas's commentary on this chapter and on chap. 8 of the second book of the *Posterior Analytics*, on which the account here is based.

itous character to the evolutionary process, and then we can be in doubt that any teleology whatever is involved in evolution. To say, on the other hand, that there are regular processes in nature whereby one species comes from another, and particularly a higher species from a lower (say, an animal from a plant), is to regard evolution itself as goal directed. Rather than arguing, for example, "If oak tree, then acorn" or "If squirrel, then squirrel-zygote," we would have to explain why it makes equal sense to speak of a developmental process whereby oak or squirrel can come from preparatory materials that would, by ordinary standards at least, be identified as "non-acorn" or "non-squirrel-zygote." In effect we would be maintaining that, whereas in the normal course of nature we find "If oak tree, then acorn" or "If squirrel, then squirrel-zygote" to be true, in the evolutionary case "If oak tree, then non-acorn" or "If squirrel, then non-squirrel-zygote" likewise holds true. And our ground for these parallel possibilities would then be that we had unveiled causal factors, hidden to date, that allow either alternative to be a valid instance of suppositional necessity—granted that different suppositions would be involved in the two cases. Assuming the fact of evolution—and for this the evidence, though indirect, is remarkably strong—its teleological status can remain but problematical until such causal factors have been isolated and identified.

1.7 The Inner Dimension

From the outset of this discussion two different but interrelated meanings of nature have been employed. By way of recapitulation it is convenient at this point to reflect on what has already been said and to identify the two. Such a reflection in turn has a twofold objective: to locate in a general way the sources of the various difficulties encountered, and to make precise the sense in which nature may be spoken of as an "inner dimension," serving to differentiate natural entities from those referred to as artifacts.

The two meanings may be approximated by observing that the one captures nature when the word is written with a capital "N," the other when it is written with a small "n." The first designates the world of nature, the universe untouched by man but of which he is a part, the object of his consideration when exploring a primeval forest or when gazing into the starry heavens. It is this sense of nature that leads one to think of the Author of Nature or of Mother Nature, of some overarching principle that puts order into a vast collection of individuals so as to make of them a cosmos. To inquire into its meaning is to raise grand questions about the origin of the universe and its ultimate destiny. Does it demand a Creator, first forming it *ex nihilo* and then guiding its development to some Omega Point that escapes human comprehension?[17] Is there an intelligent and benevolent principle behind its complex operations, more intricate in detail and vaster in expanse than anything that can be conceived, let alone devised, by man? Fascinating as these questions may be, they are obviously beyond the scope of the philosopher of nature. They are more the concern of the metaphysician or the theologian than they are of the scientist, even though the latter would be dull in the extreme not to be stimulated by them.

On further consideration we may see that such questions are the ultimates to which we are led when focusing on nature as agent and nature as end. Agent and end are extrinsic causes: in the case of an artifact they invite us to look outside the chair, for example, to ask "Who made it?" and "What for?" It surely is understandable that we are led instinctively to make similar inquiries when puzzling over the universe as a whole. The problem of evolution, in particular, brings us quickly into this domain, so it is not surprising that attempts to answer it polarize people strongly along ideological and religious lines.

The second meaning of nature focuses on the units that enter into the system of the world, that is, on particular natures found in the universe that enable things to be classified into natural kinds. Whereas questions relating to agent and end direct our thought outside the individual, as it were, questions relating to nature in this second sense turn our thought within, to a consideration of the intrinsic factors that enter into the individual's composition. This is the sense of nature that is captured by the expression "inner dimension." It is this meaning, as more tractable by the methods of scientific investigation, that is the focus of attention in most of what follows.

We tend to think of the inner dimension of natural substances as constituted by their matter and their form along the lines explained above, and this is certainly true. Both matter and form are clearly components of nature as inner sources of the characteristic properties and activities of substances themselves. And from the previous discussion of difficulties concerning them, we see that the two also raise fundamental ques-

17. The question would not have occurred to Aristotle. Despite the fact that he was convinced of the existence of a First Unmoved Mover of the universe, and even wrote of God as "Thought Thinking Itself," he had no conception of creation and simply assumed that the universe is eternal, undergoing only cyclical changes. The question would quickly arise, however, in the Judaeo-Christian-Islamic context.

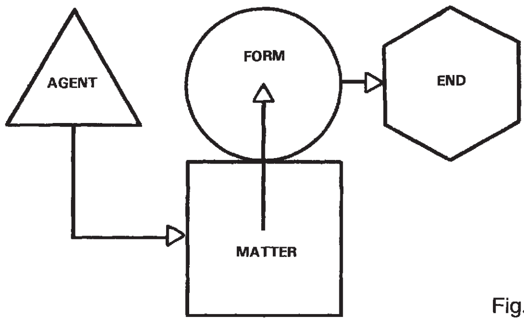

Fig. 1.1 The Causal Model

tions about the basic stuff of the universe and its organizing principles, questions no less serious than those just noted about ultimate agents and ends. Yet, as already mentioned, there are additionally agencies and finalities in nature that are not merely "out there" but also somehow "inside" or "within" the entities that make up the natural world. That is to say, the inner dimension seems to be constituted not merely of material and formal causes but of efficient and final causes as well.

To cast fuller light on this latter aspect of the inner dimension, we return to the causal model explained earlier. In the artificial analogue first used to lay out the fourfold structure of causality, an agent or efficient cause (the carpenter and his tools) worked on a particular kind of matter (oak) and shaped it into a form (say, that of a kitchen chair) that would have a distinctive finality or end (providing something comfortable to sit on, say, while eating). In this example the separation and distinction of the four causes is readily seen: the carpenter and his tools (A, for agent) are different from both the oak (M, for matter) and the shape it assumes while the chair is being made (F, for form), while the intention of making something comfortable to sit on while eating (E, for end) is different yet again. The matter and the form are in the chair when it is finished, but the carpenter is not, and his intention is not there either, except in the sense that an idea or exemplar formed part of that intention and has now materialized in the resulting product. This exception is important, however, for its identification is suggestive of the internalization of an extrinsic cause that takes place in the generation of natural forms, now to be more fully elaborated on.

Focusing for the moment only on the production of an artifact, we diagram in Fig. 1.1 the four causes just explained, using a circle and three regular polygons to show their distinction and the interrelationships between them. The agent (A) is shown as a triangle; it acts on the matter

(M), represented by a square, and is drawn as bringing forth from the matter a form (F), which in turn is diagrammed as a circle. The production of the form is itself the end (E) of the making process, which is shown as a hexagon. Thus all four causes may be seen as separate but interconnected: the agent (A) acting on the matter (M) and educing the form (F) as the end (E) of the process.

Consider now the analogous case whereby, in the order of nature and over a period of time, an adult female squirrel generates another adult female, i.e., a mature organism of the same nature as herself. Here the agent is not a carpenter but a male and female squirrel (A), the matter on which they work (M) is or has become part of their substance, and the form that they generate (F), assuming no malformation, is the same in kind as their own (A), namely, the form of a squirrel. The offspring first appears as a zygote or embryo, but over a length of time it undergoes a growth or developmental process whose end (E) is the adult squirrel. Notice, in this instance, if one glosses over the time interval between the conception and maturation of the organism generated, again assuming no accident, the form generated (F) and the end of the generative process (E) are the same. The parents and their offspring share a common nature, even though their appearances may differ markedly over time.

Again, if one concentrates on this natural form, and then considers that a squirrel is still a squirrel, that is, that all squirrels of a particular kind share the same nature despite the fact that one is not the other, it is possible to make a similar identification between agent (A) and form (F). Granted that there are individual differences between the parent squirrels (A) and their offspring (F, but also E), the same specific forms are involved in all three causes (i.e., in A, F, and E). The example brings out a point about natural forms that seems never to be verified of artificial forms. At least in some instances, a natural or unifying form (F) has within itself the potentiality of producing one or more forms identical to itself in kind (E), and thus can be the agent (A) of such a production, which as a natural process will tend to terminate uniformly in this way even though it does not do so with absolute necessity. In this way both agent (A) and end (E) come to be internalized within the natural form (F). Stated somewhat differently, such a form (F) in some way incorporates powers or agencies (A) within itself that when properly actuated will eventuate in another form already intended by nature (E) and so predetermined in advance to become that kind of substance.

With this, all the materials are at hand to clarify what is meant by nature as the inner dimension of a natural substance. The only factor left to take into account is the matter (M), and this can be done by invoking the artificial analogue yet one more time. Note now the fact that, when the oak chair has been made, the chair is the oak and the oak is the chair, that is, the form (F) has so modified the matter (M) that the two serve together as co-principles in constituting the one artifact. The situation is similar with the squirrel. Whatever the basic stuff out of which the organism is structured, whether it be molecules or atoms or the mass-energy they contain (M), the natural form has so unified those parts as to make of them one living thing that can be recognized as a squirrel (F), because it looks like one and acts like one, having agencies (A) within it to bring its powers to natural fulfillment (E). This final situation is diagrammed in Fig. 1.2, now labeled "the inner dimension." It purports to show that nature, while primarily constituted of matter (M) and form (F) as the intrinsic causes that make the substance be what it is, also incorporates agencies (A) and the functions for which they are programmed (E), all of which can be modeled by the corresponding causes of an artifact. Each cause serves as a determiner lodged within the specific nature as such and, to this extent, may be regarded as part of its inner dimension. The natural form (F), to be sure, is the dominant determiner, for it is eminently intelligible—so much so that it can be grasped, even by a youth, to serve as a starting point to unravel the factors that explain the complexity of that nature and the manifold activities to which it can give rise.

As is apparent, Fig. 1.2 shows simply how all four causes may be internalized within a natural substance (as opposed to an artifact) by enclosing within the circle that represents the natural form (F) the regular polygons used in Fig. 1.1 to designate the other three causes, agent (A), matter (M), and end (E). The diagram is only schematic, and its purpose is not to represent natures in general; rather its focus is on the specific nature of a higher mammal such as a squirrel. Even then the nature depicted is thought of not as individual but as common and specific, common to the parents and offspring of a family and to a particular species. In this representation the basic matter or mass-energy (M) of each organism is its nature, the co-principle within it that makes it a material substance, capable of subsisting as an individual and initiating various activities as well as being receptive of them. The natural form (F) is also the organism's nature, and even more so, since form is a complementary co-principle, activat-

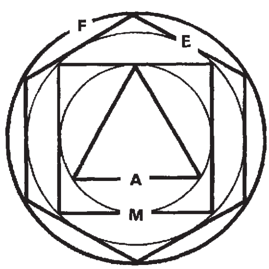

Fig. 1.2 The Inner Dimension

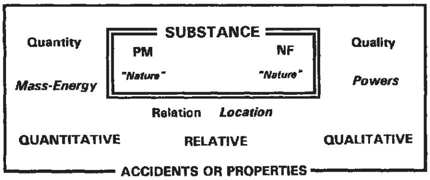

Fig. 1.3 The Individual Natural Body

ing the mass-energy and determining the matter, contracting its potentialities, as it were, to being a substance of a particular type, then stabilizing the substance in such being and supporting its distinctive powers and activities. Among these powers is the nature itself as agent (A), as a source of activity that includes the ability to replicate, to produce another nature similar to its own through the reproductive process. And finally, when this new nature is produced as the end of the process (E), the same nature terminates the process and so may additionally be designated its final cause. Thus all four causes come to be internalized within the concept of nature, even though only the material cause and the formal cause may be spoken of as internal causes in the strict sense.[18]

1.8 The Individual Natural Body

To move now from the level of specific natures to that of individual natures, we are in a position to summarize much of what has been said thus far by rearranging in more expanded form the information contained in Figs. 1.1 and 1.2. The purpose of the new arrangement is to elaborate further on how one may regard matter and form as internal causes while allowing agency and finality also to be lodged within an individual natural body. It makes use of the ontological distinction between substance and accident, and the further distinction between a proper accident and an adventitious accident,[19] to explicate in more detail how the four-ply structure of causality actually functions within an individual substance.

18. Fig. 1.2 may thus be seen as applying to the squirrel, as already noted, in that the squirrel's nature functions as an efficient, material, formal, and final cause in the generation of a new individual of its species. In a more general way it may be applied to any physical nature whatever, in the sense that a complete definition of the nature would include a specification of all four of its causes and thus would include not only its matter and form, but also the agent that produced it and the end that terminates its production.

19. In the ontological order, as discussed in Aristotle's *Categories*, an accident is an entity that does not subsist by itself but exists in another. In the order of predica-

The new arrangement is shown in Fig. 1.3. Like the two previous representations, this is not a pictorial or iconic model, but rather may be thought of as an epistemic model of a special type. We might call this an ontic model—essentially a schematic way of representing ontological factors that bear on the operations of natural substances. As diagrammed there, an individual natural body is composed of substance and accidents, the first enclosed in double outline and the second, entitled "accidents or properties," in single outline. Its substance, shown as the inner core, is itself composed, the two essential components being matter and form, with the letters PM and NF now replacing our earlier M and F. PM stands for protomatter, Aristotle's *hulē prōtē* or *materia prima* of the Latins, and NF for natural form, Aristotle's *morphē* or *natura* of the Latins. Alternate ways of designating this form are substantial form (the *forma substantialis* of the Latins), or again, specifying form, or yet again, stabilizing form. The reason for our preferring natural form over the alternative terms is indicated below the letters in the diagram, namely, that both NF and PM can be referred to as nature: for Aristotle the first is nature in the primary sense as actual, whereas the second is nature in a secondary sense as potential.[20] The actual nature of a thing or its natural form is what specifies it as a natural kind and further stabilizes it in being. Thus the NF not only informs the PM and makes of it a composite substance, but it also makes the substance be what it is, that is, it organizes and specifies it. Again, the form confers on the protomatter a stable mode of being, so that the composite it forms, the natural substance, underlies its accidents in more than transitory fashion.

The accidents of a natural body are then shown, arranged somewhat arbitrarily around the inner core. They are grouped into three categories:

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tion, however, an entity that exists in another may be part of the being of that other, and so would be predicated of it as one of its properties or proper accidents, or it may be non-essential or adventitous, in which case it would be predicated merely as an accident and not as a property. These two ways of predicating are differentiated in Books 2, 3, and 5 of Aristotle's *Topics*.

20. Aristotle lays the groundwork for this identification in chaps. 7 through 9 of the first book of the *Physics*, where he refers to matter as the "underlying nature" (191a8) and form as the "natural form" (192b1). He elaborates further on this in chaps. 1 and 2 of the second book, where, having given his definition of nature (see note 1 above), he goes on to state: "One way, then of regarding nature is as the first underlying matter . . . ; from another point of view we may think of the nature of a thing as residing rather in its form, that is to say, in the 'kind' of thing it is by definition" (193a28–31). Later he explicitly affirms that "the form is nature to a higher degree than the matter," and gives as his reason that "each thing receives a name when it exists in actuality rather than when it exists potentially" (193b7–9).

quantitative, qualitative, and relative. The most important of the first group is quantity itself, shown next to protomatter, and the most important of the second is quality, shown next to the specifying form. The relative accidents then include relation and the last six species of accident listed in Aristotle's *Categories*, of which only one, location, is shown on the diagram.[21]

With regard to quantity, we may note that its basic function as an accident is to ground bodily extension by putting part outside of part and so enabling matter or substance to be divisible into parts. Such parts can then be conceptualized as discrete and so become the basis for numbering in the order of nature. On this ground there are two kinds of quantity: continuous, associated with magnitude or extension, as in the length of a line; and discrete, associated with multitude or number, as in a positive whole integer. Medieval commentators on Aristotle, such as Thomas Aquinas, also saw extensive quantity, when taken together with protomatter (*materia signata quantitate*, matter signed with quantity), as the individuating principle in a natural substance (this will be explained in Sec. 2.6 below).[22] In the late seventeenth century, Isaac Newton focused on the related concept of "quantity of matter" (*quantitas materiae*) and thought of it as mass.[23] More recent science has furnished the broader concept of mass-energy—which we have proposed as a surrogate for protomatter, its quantitative measure, as it were—shown beneath quantity on the left of the diagram.

21. The location referred to here is location in space; the other five remaining categories are action, reception, location in time, situation, and possession. These are all listed in chap. 9 of the *Categories*. All of these terms, including those from Aristotle's *Physics* mentioned in previous notes, are of course difficult for the modern reader to assimilate and comprehend. Throughout history, in fact, the *Physics* has been referred to by its Latin title, *Physica ex auditu* (literally "Physics from hearing"), to indicate that it can be learned only with the aid of a teacher. Thus the reader who wishes to go beyond the schematic presentations used in this study to gain a deeper understanding of the concepts they introduce should have recourse to one or more textbooks that teach Aristotelian natural philosophy. The best reference for our purposes is Vincent E. Smith, *The Science of Nature: An Introduction*, Milwaukee: Bruce Publishing Company, 1966, pp. 1–128. This is an abridgment of Smith's *The General Science of Nature*, Milwaukee: Bruce Publishing Company, 1958, which provides a fuller account.

22. See Aquinas's *Summa theologiae*, First Part, quest. 75, art. 4.

23. Thus his first definition in the *Principia* reads: "The quantity of matter is the measure of the same, arising from its density and bulk conjointly." Then, in explaining the definition, he states, "It is this quantity that I mean hereafter everywhere under the name of body or mass."

As a proper accident, quality stands for the distinctive attributes of an object through which we come to know its nature. There are various ways of classifying qualities: the most obvious kinds are sensible qualities, those that fall directly under the senses such as a particular color, temperature, odor, and taste, and the particular shape or figure a body assumes, such as the outline of a cat. These collectively make up the accidental features through which we differentiate one individual from another—its individuating characteristics—while being aware that they are not essential to the nature itself. Less obvious are the various powers or dispositions with which substances are equipped and which are more directly linked to their natures; it is from the exercise of such powers that their natures can be ascertained. On this account, since a thing's actions and reactions enable us to determine its powers, and from these we judge its nature or say what it is, we here regard its powers as proper accidents or properties. We thus indicate only powers as representative of the distinctive attributes in which we shall henceforth be interested, and show it below quality on the right of the diagram.

This last consideration, which assumes importance for understanding the various ontic models to be proposed in what follows, points our way to rejoining the problem of extrinsic causality and showing how this is related to the concept of nature. The ontic models to be detailed will schematize the relationships between characteristic activities, natural powers, and the stable natures that are their underlying source. Stable natures we shall consider as pertaining to three broad genera: inorganic natures, plant natures, and animal natures; in addition we shall treat of human nature as adding a further specification to animal nature. All are stable in the sense that substances with these natures have a fairly permanent mode of being and acting; they are to be distinguished from transient entities, about which more will be said in the following chapter. The key differentiation, however, lies in the characteristic activities and reactivities that are proper to the various genera. These proceed from agencies or powers located within species subsumable under each genus and on this account are intrinsic to both the genus and the species. At the same time such powers are what enable the individual bodies that instantiate the species to be agents acting on other things and so incorporating within themselves the notion of agency (A) or efficient cause. In thus acting they achieve ends (E) consonant with their natures and so give indication of the many ways in which nature is teleological or acts for an end. Through them, therefore, we can go beyond seeing nature as restricted only to matter (M) and form (F), as though nature were to function as an intrinsic cause alone. They enable us to see nature as both agent and end along the lines sketched above, and thus as involving elements of extrinsic causality as well.

1.9 Models of Various Natures

How this can be done for each of the genera requires further explication and exemplification, to be undertaken in the chapters that follow. A general idea, however, can be gathered from Fig. 1.4, which represents a powers model of various natures. The basic polarity of PM and NF, that is, of protomatter and natural form, structures this figure just as it does Fig. 1.3. The main difference is that Fig. 1.4 separates the two vertically rather than horizontally and then shows the four different kinds of natural form, designated by the different subscripts attached to the letters NF across the top. The first or lowest order, indicated by NF_i, with the subscript "i" standing for inorganic, determines the protomatter to be a substance with an inorganic nature; that next to the right, indicated by NF_p, with the subscript "p" standing for plant, determines the protomatter to be a substance with a plant nature; that to the right of it, indicated by NF_a, with the subscript "a" standing for animal, determines the protomatter to be a substance with an animal nature; and that last to the right, indicated by NF_h, with the subscript "h" standing for human, determines the protomatter to be a substance with a human nature. Within each of these types, with the exception of the last, there is the possibility of many different species. Thus, among inorganic substances we might have copper or sulphur; among plants, geraniums or oaks; among

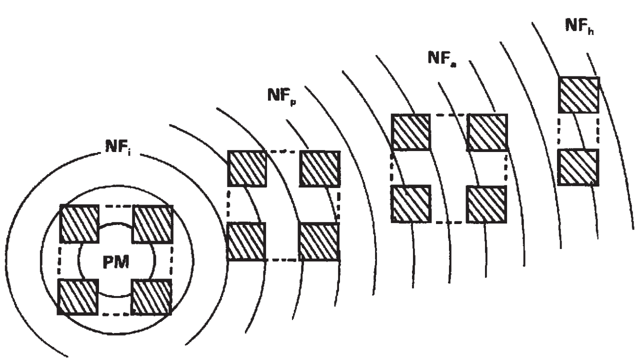

Fig. 1.4 A Powers Model of Various Natures

animals, squirrels or cows, and so on. The natural form is said to be a specifying form because it determines the substance to have a particular nature, that of copper or sulphur, geranium or oak, squirrel or cow. In fact, as its name indicates, the natural form itself may be referred to as the nature of the substance it determines. And we recognize this when we observe a particular substance and note its nature, saying this is copper, that is an oak, and the animal running there is a squirrel. A nature, moreover, is a durable thing, and that is why we can speak of a substantial form as a stabilizing form. If a substance is copper, or oak, or a squirrel, it is not a transient entity but tends to stay that way—copper perhaps for years or centuries, the oak and the squirrel over their life spans.

Apart from surface appearances, we further categorize natures on the basis of the powers from which the activities or reactivities of various substances originate. This is indicated in Fig. 1.4, where the cross-hatched boxes grouped under the four NF's are the powers proper to each NF. There are four of these for the first three types of NF and only two for the last. Identifying and explaining each of these is the task set for the following chapters. Here we would merely state that all of these powers, except the two that are proper to the human form (NF_h), require bodily parts or organs for their operation. That is why plants and animals are called organisms, for their bodies are differentiated into organs with which they perform various life functions. The organs are parts of their bodies; the powers that activate or energize them may be thought of as parts of their natural forms, so let us call them "power parts" to distinguish them from bodily parts. Inorganic substances, of course, do not have organs in the proper sense, but they do have parts that are roughly equivalent—molecules, atoms, nuclei, electrons—all controlled by the four basic forces or powers that we might say "energize" the world of the nonliving.

Notice now a curious feature of Fig. 1.4. It may be viewed as modeling four different kinds of natural substance, or it may be seen as picturing only one particular kind of substance, depending on how much of the figure is taken into account. But, when considering any one kind of substance, note this further fact: one can disregard the powers that are found on its right, but one is forced to take into account the powers that are found on its left. A plant, for example, shown as NF_p, does not have the powers of sensation and movement that are found in animals, and so these are not required for its understanding. Yet, as biochemistry has taught us, it cannot exercise its powers of nutrition and growth if it is not a physico-chemical composite endowed with the basic forces of the inorganic. Similarly, a brute animal, shown as NF_a, does not have the reasoning powers found in a human, but it cannot be an animal if it does not have vegetative powers as well as the physico-chemical powers on which the latter depend. And finally, the human being, shown as NF_h farthest on the right, requires all the powers on the left to carry out its life functions. The human substance is at once human, and animal, and plant, and inorganic. Thus the human form includes virtually within itself an animal form, a plant form, and an inorganic form, and so it contains all their powers as power parts. Through them it is able to energize its many bodily parts, the organs and components of which the human body is composed.

With this we return to the problem that has been engaging us in the last two sections and ask, once again, where the two extrinsic causes, agency and finality, are contained within nature as part of its inner dimension. Note now that, apart from the letters and boxes in Fig. 1.4, we have also included circular lines to create the impression of a field radiating out from protomatter (PM). That field should be thought of as an activating or energizing field, and indeed as a model of the natural form (NF) itself, for the natural form is what activates or energizes its underlying matter. Not only does the form energize matter to form the body, as it were, but it also energizes the various activities in which the body comes to be engaged. But the natural form, as its name indicates, is strictly speaking a formal cause, and so we have to be careful when labeling it an efficient cause. The reason for this is that the natural form does not produce any activity *directly*; rather it does so through the powers that, ontologically speaking, are its proper accidents. The form acts, but only *through* the natural powers it possesses, and it is in this way that agency can be attributed to it. And when it acts in this way, it acts for ends that are consonant with the nature it forms, and on this account it can also be seen as a final cause. Thus finality comes to be included within nature itself, and in a surprising way, under the concept of form. Not that the formal cause is strictly speaking a final cause, but rather that natures as forms are possessed of powers that are end-directed, and such forms presuppose agency and finality for their very understanding.[24]

Our next task is to explore the powers that are characteristic of the

24. For particulars on how natural forms may be modeled as energizing fields, see the detailed discussions below: for inorganic forms, Sec. 2.9 and Fig. 2.6; for plant forms, Sec. 3.4 and Fig. 3.5; for animal forms, Secs. 3.6 and 3.7 and Fig. 3.10; and for the human form, Sec. 5.1 and Fig. 5.1.

various natures, now to fill in, as it were, the cross-hatched boxes in Fig. 1.4. In doing so we shall start with the natural forms that are closest to protomatter and build up, from ground zero, more detailed models: first that of an inorganic nature, then those of plant and animal natures, and finally that of human nature itself.

2 Modeling the Inorganic

To speak of the inanimate world is to presume that there is a difference between the living and the nonliving and that this difference is easily recognized. Now admittedly there are natural entities whose kind is difficult to establish and which thus might leave us in doubt whether life can be predicated of them. But most specimens encountered in normal surroundings do not present this difficulty: we classify them as plant or animal if they manifest vital activities at one level or another, and if not, we regard them as inorganic. Ores and minerals fall in the latter category; they have nothing in common with daffodils and chipmunks that would lead us to see them as animate. Planets and stars, on the other hand, present more of a puzzle for not being close at hand. Yet with few exceptions, civilized peoples have tended to include them among the nonliving, since they give no indication of undergoing the changes associated with life processes. Thus the inorganic world is commonly thought to be made up of chemical elements and compounds, of crystals and minerals of various types, of heavenly bodies, and then of the various particles of which all these might be composed, such as molecules, atoms, electrons, and so on. It is this type of entity whose natures we here consider and propose to model.[1]

1. This account is similar to Aristotle's, the main difference being in the way he conceived the elemental components of terrestrial and celestial bodies. Terrestrial bodies, for him, were composed of the four elements (fire, air, water, and earth) in varying proportions; the elements, in turn, were simple and uncomposed of integral parts (unlike our chemical elements), although they were composed of protomatter and natural form as essential parts, like all material bodies. Heavenly bodies, on the other hand were composed of a fifth element (the *quinta essentia* or quintessence). Whether the protomatter that entered into their composition was the same as that in material bodies is not clear in Aristotle's text and was much disputed among his commentators.

If nature, as described in the previous chapter, is the inner dimension or inner source of characteristic activities and properties, we can see right away the problem posed when modeling the inorganic. As opposed to the animate, inanimate objects have little activity that can serve to reveal the natures that are within them. Living things give some indication of their capacity to initiate activity from within, such as growing, reproducing, and moving about. Nonliving things tend to be inert, and observation alone seems powerless to reveal any powers within them for initiating and terminating changes characteristic of their types.

With so little to go on, the ancients concentrated on sensible qualities, on the ways substances affect the senses, as primary indicators of basic kinds. The various pairings of the couplets hot-cold and wet-dry led them first to regard earth, water, and air as the three basic elements, with earth dry and cold, water wet and cold, and air wet and hot; to these they assimilated fire as a fourth element, thinking it to be dry and hot, even though its status as a substance was not immediately clear. Such a classification not only agreed with the way these materials were perceived by the senses but also fitted well with the natural motions the elements were thought to undergo. Earth was seen as heaviest, for when unsupported it spontaneously moves downward in water and air; water and air were thought to be partly heavy and partly light, for water goes downward in air and upward in earth, whereas air goes upward in both earth and water but downward in fire; fire, lastly, was regarded as lightest of all, since it moves upward through the other three. Compound or mixed bodies generally supported these conclusions, for all substances seemed to contain heat or moisture in varying degrees and manifested specific gravities of varying amounts, depending on their particular elemental constituents.[2]

In the modern period considerably more evidence became available, for, with the birth of chemistry, experimentation was added to observation and new data were quickly amassed. Of special importance was the study of the ways substances react to one another when placed in solution or in close contact, for in such situations they display more activity than when studied alone. The development of astronomy and astrophysics, particularly with the aid of instruments such as the telescope and the spectroscope, also brought the heavenly bodies closer and

2. The details of this general configuration are worked out by Aristotle in his *On the Heavens* and *On Coming to Be and Passing Away*, works frequently cited by their Latin titles, *De caelo* and *De generatione et corruptione*.

showed them to have components similar to those of objects of which we have direct experience.[3]

Yet, because of the smallness of atoms and the remoteness of stars, it proved difficult to grasp the nature of either—surely more enigmatic than those of plants and animals. Gold, silver, and lead, together with carbon, sulphur, and a few other substances, were soon recognized as elements, appearing to the senses as completely homogeneous. So, of course, did compounds such as ice, salt, and emerald, and unless one had ways of examining the microstructure of these materials there was little prospect of assessing their elemental composition.

Again, in the plant and animal kingdoms it is possible not only to identify natural kinds but also to distinguish individuals within those kinds. Numerical identity is not so apparent in the realm of the inorganic. We tend to think of all hydrogen atoms and electrons as the same, *exactly* the same, whereas we would never think of daisies and cats in that way. Is this because elemental objects are so simple that they lack individuating characteristics, or is it because we know so little about them that we simply assume them to be the same?

These considerations prompt a return to the theme of the previous chapter. In the world of nature generally we do not grasp the natures of things immediately; rather we come to know them progressively as we familiarize ourselves with their characteristics. Modeling has a special role to play in this task, and this becomes particularly true in the study of the nonliving. Inorganic natures are less complex than the organic, and this turns out to be an advantage: our models will have fewer attributes or notes to take into account, so it becomes possible to focus more on questions relating to their unifying form and their ultimate substrate. At the same time there are distinctive powers and reactivities to be investigated in this domain. These enable us to explore the agents and reagents associated with natural forms, to see in what ways such forms can be the inner sources of inanimate activity.

3. Dark lines in the sun's spectrum were first observed by William Wollaston in 1802, but their significance was overlooked until Joseph von Fraunhofer mapped its many lines in 1814. In 1862, using the previous work of Robert Bunsen and Gustav Kirchhoff, Anders Ångström detected the presence of an element in the sun (hydrogen) from a study of the solar spectrum.

2.1 Elements and Compounds

How the four terrestrial elements of the ancients came to be replaced by the ninety-odd naturally occuring chemical elements found in the periodic table may now be sketched in summary fashion.[4] It seems that the element fire, always problematical because of its aetherial quality, was the first to yield to attack, during seventeenth-century studies of combustion. Its mystery was solved when burning was found to be an oxidation process, which in turn led to the discoveries that the element air is actually a mixture of oxygen and nitrogen and that the element water is itself a composite of oxygen and hydrogen. Carbon then manifested itself in "fixed air," i.e., carbon dioxide. In its solid state this substance and countless others classified as metals and nonmetals, were found to be the principal constituents of the element earth. Thus one of the four ancient elements was eliminated and the other three were shown to be composites of yet others in varying degrees of complexity.

Experimentation and measurement provided the route to all these discoveries. One of the earliest procedures consisted in isolating various substances in the gaseous state, finding out ways they could be made to combine, and then measuring the precise weights and volumes that entered into combination. Repeated confirmation and analysis of such measurements led to the conclusions that over ninety unit atomic weights are discoverable in nature, one for each chemical element, and that vaster numbers of unit molecular weights, one for each chemical compound, are found in nature also. Unit atomic weights by definition had their counterparts in atoms and unit molecular weights had theirs in molecules. Thus it was that elements came to be identified with atoms of various types, and compounds in turn with molecules resulting from the almost innumerable ways atoms came to combine under the proper conditions.[5]

The concepts of atom and molecule are so firmly entrenched in modern thought that we tend to replace the concepts of element and com-

4. Whereas the revolution in physics took place largely in the seventeenth century, that in chemistry did not occur until the end of the eighteenth century and the beginning of the nineteenth, the main contributors being Priestley, Lavoisier, Dalton, Gay-Lussac, and Avogadro. Dalton's *New System of Chemical Philosophy* was completed in 1810; Avogadro's clarification of the concept of molecule and his announcement of the law that bears his name appeared in 1811.

5. John Dalton first proposed his atomic theory of matter in 1803 on the basis that chemicals combine in integral proportions by weight, and late in 1808 Joseph-Louis Gay-Lussac announced that gases combine chemically in definite proportions by vol-

pound by them, forgetting that the direct objects of the chemist's consideration are not minute particles but naturally occuring substances that fall under sense experience. The water that is broken down by electrolysis into hydrogen and oxygen is the same water found in wells, streams, and lakes; the copper and sulphur that combine to form copper sulphate, or the iron filings that oxidize in the atmosphere to form iron oxide, are elements that in their raw or combined state can be dug from the earth. These are not artifacts, nor are the changes they undergo artificial processes. The experimenter is not the ultimate determiner of how much of one reagent will enter into combination with another, although to perform the experiment properly he must ensure that sufficient quantities of both are present to make combination possible. Rather the laws of combining weights and combining volumes are generalizations that apply directly to the workings of nature. They record how the substances involved themselves determine not only the quantities that combine but also those that turn up in the end product. Again, we spontaneously think of the atom as the natural minimal part of an elemental substance or the molecule as the natural minimal part of a composite substance. Yet we need to remind ourselves that our sense knowledge bears on elements and compounds alone, that if we can be said to know atoms and molecules at all we know them only in a quite indirect way.

To be able to identify atoms and molecules even on this basis, however, is a remarkable achievement, for it enables data to be gathered about the ways in which chemicals build up and break down, the characteristics that families of elements have in common, and the properties that are likely to be found in the compounds that result from them. As organized in the periodic table, such information enables chemists to detect natural kinds in the realm of the inorganic similar to those long known to botanists and zoologists in the realm of the organic. And possibly because of the greater simplicity of their subject matter, plus its amenability to experimentation and to the use of quantitative techniques, this has led chemists to make other advances more rapidly. Typical of these are grasping why various elements can be grouped periodically and what there is about them that causes them to enter into some reactions but not into others. While taking longer to be discovered, chemical kinds once identified have come in some ways to be better un-

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ume. The two results appeared to conflict on the amounts of hydrogen and oxygen involved in the composition of water. The difficulty was partially resolved by Amedeo Avogadro in 1811, but it was not until the late 1850s that Stanislao Cannizzaro worked out its definitive solution on the basis of atomic masses. See Sec. 9.7 below.

derstood than biological kinds known to mankind for well over twenty centuries.

2.2 Elemental Constituents

The key discovery that enabled the secrets of the periodic table to be unlocked was that of electric charge, first as encountered in experiments with electrolysis and then as further isolated with the discovery of the electron toward the end of the nineteenth century.[6] The electron is a unit negative charge of very small mass that can explain many electrical phenomena; it is also believed to be an important component of the atom. But the atom, or the element whose natural minimum it is, itself gives indication of being electrically neutral. On this account it would appear that any negative electricity situated within it must be offset by a corresponding amount of positive electricity located there also. Attempts to situate where such positive charge might reside led to a planetary model of the atom, in which most of the atom's mass was seen to be lodged in a positively charged central nucleus; this nucleus was in turn pictured as surrounded by peripheral electrons, the latter equal in number to the positive charges they counterbalance.[7] Moreover, when arranged in order of increasing atomic weights the chemical elements (and the atoms corresponding to them), were found to manifest properties that recur in groups or periods. From the way in which atomic weights increased from element to element throughout the resulting periodicity, it was further inferred that the atomic nuclei themselves contain two kinds of particles, each of roughly the same mass. These two kinds are called protons and neutrons, the first bearing a unit positive charge and the second

6. The first electrolysis of water, reversing earlier experiments showing that water was generated by the combination of hydrogen and oxygen, was performed in 1800 by William Nicholson and Anthony Carlisle. By 1833 Michael Faraday had formulated a basic law of electrolysis relating the amount of substance decomposed to the amount of current used over a period of time. In 1897 J. J. Thomson discovered the electron, and around 1906 Robert Millikan began the oil-drop experiments with which he determined the charge on the electron and for which he was awarded the Nobel Prize in 1923.

7. This model of the atom was proposed by Ernest Rutherford in 1911. Earlier, in 1904, the Japanese physicist Hantaro Nagaoka had speculated that atoms might look like the planet Saturn, with rings of electrons circling a positive core. On the basis of experimental evidence Rutherford emended this to have the atom more resemble the solar system than Saturn, with only a few electrons moving around the nucleus in circular orbits.

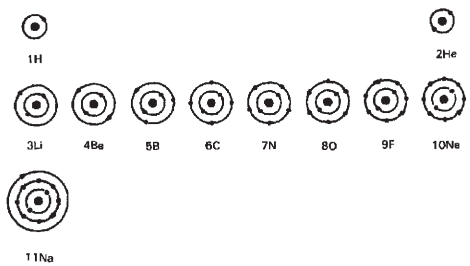

Fig. 2.1 Electron Orbits of Elements in the Periodic Table

electrically neutral. On this accounting the number of protons in an atom's nucleus then corresponds to the number of electrons located in its periphery, while the number of neutrons corresponds to whatever additional mass must be added to that of the protons to make up the element's overall atomic weight.[8]

What has just been described is a model of the atom that conceives it as a solar system in miniature, with the nucleus analogous to the sun and electrons to the planets revolving around it. Unlike the causal or ontic model discussed in the previous chapter, however, this is a pictorial or iconic model: it provides a picture or representation of the inner structure of the atom, showing how its nucleus and orbiting electrons are thought to be arranged in space. Further theorizing about this model has led to the introduction of various circles or shells in which electrons are distributed around the nucleus, and to the localization of the outermost electrons that serve to explain the valences and affinities manifested by the various elements, as shown in Fig. 2.1. This shows schematically the arrangement of the electron orbits of the first eleven elements in the periodic table. The first row, containing only hydrogen and helium, has but one shell, whereas the second row, containing the elements from lithium to neon, has two shells, and the third row, shown beginning with sodium, has three shells. Through the use of this amplified model it is possible to give a theoretical justification for the law of combining weights. We can also explain why chemical elements combine the way they do, in fixed and constant proportions, as the atoms of interacting reagents share or exchange electrons to complete their outermost shells. In this way we can even visualize chemical bonding, with electrical or electromagnetic forces serving to unite atoms within molecules, and so explain the struc-

8. The proton was discovered by Ernest Rutherford in 1914 and the neutron by James Chadwick in 1932.

ture of molecules and the various molecular masses that result from the combination of their constituent atoms.[9]

This planetary model of the atom proved so successful in chemistry, particularly for providing a theoretical understanding of the periodic table of the elements, that physicists became interested in it also, specifically for the prospect of its explaining how elements absorb and radiate electromagnetic energy. It was in this sphere of investigation, spurred on by the quantum theory first proposed by Max Planck, that the most spectacular discoveries of the twentieth century relating to the structure of matter were made.[10] According to nineteenth-century theories of electromagnetism, if electrons circle a positively charged nucleus they will continuously radiate energy and ultimately will fall into the nucleus, thus destroying the atom's structure. To avert this end and maintain the atom's stability, while also explaining how it can absorb and emit discrete amounts of radiation in line with Planck's theory, Niels Bohr proposed a quantized model of the atom.[11] In this model electrons move in stable orbits within their shells without emitting or absorbing radiation, as they would in classical electromagnetic theory. Under the influence of strong electrical fields or other external energy, however, electrons can make stepwise jumps from one shell to another. Bohr speculated that when an electron moves farther from the nucleus in this way it absorbs an amount of electromagnetism determined by the different energy levels of the two orbits; when it drops from an outer orbit to an inner one, it emits a similar amount. By formulating a series of rules stating which electron transitions are allowed and which are not, Bohr found that he could explain the emission and absorption spectra of many chemical el-

9. The concepts of valence and bonding were introduced into chemistry around the middle of the nineteenth century; they were used by August Kekulé for diagramming the structure of organic compounds in 1861.

10. The notion of the quantum was introduced into physics in 1900 by Planck in an attempt to solve anomalies in black-body radiation arising from experiments performed in the 1890s by Wilhelm Wien and Lord Rayleigh. Planck found that these anomalies would disappear if it was assumed that electromagnetic radiation can only be emitted in energy packets of very small size, which he called quanta. The concept began to gain acceptance after 1905, the year in which Albert Einstein used it successfully to explain the photoelectric effect.

11. Bohr began working out the details of this model for the hydrogen atom, the simplest case wherein a single electron orbits a proton, in 1913. He found that theory and experiment could be reconciled if the value of the quantum was used to restrict the motion of the electron to discrete orbits around the proton. In his model each of these energy states would be defined by a particular whole number which he called a quantum number.

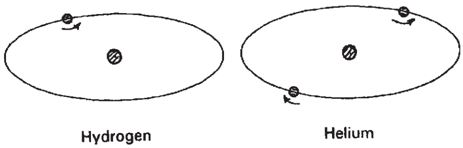

Fig. 2.2 Electron Orbits in the Hydrogen and Helium Atoms

ements. In effect, he could correlate the wavelength and intensity of the radiation characteristic of a particular element with the jumping of electrons in the atomic model of that element from one stable orbit to another.

Further refinements of Bohr's model included the replacement of circular orbits by elliptical orbits and then, along with that, the possibility of the orbits having various orientations in three-dimensional space to provide additional possibilities for stable electron paths, also referred to as energy states.[12] Another was the introduction of electron spin, that is, a rotation of an electron on its own axis, to define still more energy states. Yet another was the introduction of a principle by Wolfgang Pauli specifying that no two electrons in an atom can occupy the same energy state at any one time, as illustrated in Fig. 2.2.[13] Here are pictured the electrons in the first shell of hydrogen and helium respectively. The single electron of hydrogen is shown with a clockwise spin, whereas the two electrons of helium are shown with a clockwise and a counterclockwise spin. According to Pauli's principle, two electrons may occupy the same shell only if they have opposite spins. With each advance, physicists thus seemed to have a more graphic picture of the structural components of each element, and in terms of that picture could account for most of its chemical and electromagnetic properties.

The Bohr model of the atom, as it came to be called, stimulated vast research programs that offered hope of one day providing detailed and

12. Around 1915 Arnold Sommerfeld modified Bohr's model to have electrons follow elliptical rather than circular orbits around the nucleus, and this introduced a second quantum number into the theory. Next it was found that atomic spectra are affected by magnetism (the Zeeman effect), and this led to the postulation of a third quantum number to take account of the magnetic state of the orbiting electrons.

13. The concept of electron spin was introduced by George Uhlenbeck and Samuel Goudsmit in 1925, and this provided a fourth quantum number for the emended Bohr atom. At that time it was thought that all four numbers, if known, would suffice to provide a precise description of an electron in its orbit around the nucleus. In the same year Wolfgang Pauli formulated his Exclusion Principle, stating that no two electrons in an atom can have the same quantum numbers (or occupy the same energy state within the atom) at the same time.

authentic representations of the microstructure of matter. As these programs were pursued, however, they ran into difficulties. Typical was the discovery that electrons, which in the model were conceived as charged spherical particles, behave as waves in some experiments.[14] Now waves are more difficult to visualize than particles, and it is no simple matter to associate spin with them as one might with a sphere. Other problems came from applying Einstein's theory of relativity to the movement of particles within the atom. The need to employ multidimensional spaces led to the introduction of models that were more mathematical in character, which in turn defied attempts at visualization in Euclidean space. Thus Bohr's quantum mechanics gave way to wave mechanics and then to matrix mechanics, with each theoretical advance making the atom less picturable, though better adapted for quantitative predictions of the behavioral characteristics of the element with which it was associated.[15]

The recognition of these limitations in the Bohr model fortunately did not deal a devastating blow to knowledge of the inorganic. The difficulties it encountered were concerned more with iconographic details than they were with the gross features of atomic structure. However we picture electrons and protons and neutrons, we can be fairly certain that they are in some way the constituents of atoms and molecules. The dimensions of atoms and molecules can even be calculated with some degree of accuracy, and the approximate arrangement of atoms within molecules and of molecules within crystals can be ascertained.[16] Most

14. Already in 1923 Louis de Broglie had proposed that an electron or other subatomic particle might behave either as a particle or as a wave, thus introducing the concept of particle-wave duality into the theory of matter, paralleling its use in electromagnetic theory. His theory was confirmed by Clinton Davisson in 1927, when he showed that electrons can be diffracted by crystals just as can light rays. A year earlier Erwin Schrödinger wrote the first paper on wave mechanics; in it he applied de Broglie's theory to the structure of the atom, replacing electron orbits in the Bohr atom by wave trains that appear as solutions to the wave equation known by his name.

15. Matrix mechanics is usually associated with the name of Werner Heisenberg, who in 1927 formulated his Uncertainty Principle, according to which it is theoretically impossible to determine the position and the momentum of an electron at the same time. His new theory, aided by the work of Paul Dirac, was able to overcome some of the limitations of Schrödinger's wave equation, which does not take electron spin or the theory of relativity into account. Mathematically it is so complicated, however, that most physicists continue to use Schrödinger's equation in its place. Following a suggestion of Max Born, they now interpret the equation as providing the probability that an electron is located in a particular orbit rather than as giving a precise description of the electric charge distribution within the atom.

16. How this is done will be explained in the following chapter.

of the phenomena of modern chemistry can be understood and visualized through the use of the Bohr model, and if properly interpreted it continues to provide a working insight into the elements that make up the universe.

2.3 The Inorganic Form

Returning to the causal, nonpictorial model with which we have earlier been concerned, we now begin to explain how the Bohr model may cast light on the nature or inner dimension of an inorganic substance. Of the four causal factors involved in that model, it has been noted that the form or formal cause is the most intelligible, and this is the point at which we start.

The element sodium was discovered at the beginning of the nineteenth century; [17] it is the sixth most abundant element on earth, found especially in common salt and sea water. In its isolated state it is a light, silvery-white, soft metal that can be cut with a knife at room temperature. Chemists classify it among the alkali metals since it has characteristics similar to lithium and potassium. It is very active chemically, combining with the oxygen of the air and reacting vigorously with any water with which it comes in contact. For this reason it is usually kept immersed in an inert liquid such as kerosene. Like other metals sodium conducts heat and electricity easily, but unlike others it emits electrons readily when exposed to light. When burned in a flame or in a sodium vapor lamp it shines with a strong yellow light. Etc., etc.

A person who has seen this peculiar metal (rare because its very activity works against its being found in an uncombined state), and particularly one who has experimented with its many properties, can be said to know the nature of sodium. But what does he know when he knows that nature? Assuming that the nature has a formal and a material component, as already explained, it is difficult to see how he knows the matter directly. At best he can model it as found in the Bohr atom and say that sodium is formed out of electrons, protons, and neutrons arranged in a special way. And this is not too helpful, for the stuff of which their components are made is not directly known, and this very same material composition, from the point of view of the matter, can be attributed to other elements in the periodic table. If the Bohr model tells anything,

17. The English scientist Humphrey Davy discovered potassium by the electrolysis of potash on October 6, 1807, and a week later discovered sodium by the electrolysis of soda.

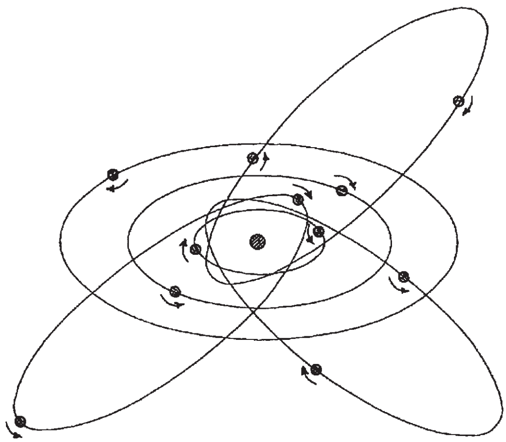

Fig. 2.3 Electron Orbits in the Sodium Atom

therefore, it is that the organization or formal arrangement of these components, and not the components themselves, makes sodium be what it is. The facts that its nucleus is composed of twelve neutrons and eleven protons and that the atom contains eleven orbital electrons—two in the first shell, eight in the second, and the remaining one the valence electron of the third, all shown in Fig. 2.3—serve to explain the many properties outlined above. The simplified electron shells of sodium (Na) shown in Fig. 2.1 are here replaced with elliptical orbits having different orientations in space and each containing two electrons of opposite spin.

This arrangement of the components, it should be stressed, is not an artificial form, like the shape of a chair imposed on pieces of wood that maintain their own identity. One who comprehends the Bohr model must see that none of the three components of the sodium atom acts simply as an electron, proton, or neutron, that each functions instead as a part of sodium. The form that is known and that is modeled in the Bohr atom is therefore a natural form, a unifying form that confers substantial identity on the parts that make up the composite. Traditionally this has been called the substantial or substancing form, but as noted earlier it can equally be regarded as a specifying form and a stabilizing form. It gives unity to the parts by specifying the substance they compose as sodium, and it stabilizes them by rearranging them, when necessary, to maintain that element's specific identity.

To make more explicit this integrating and organizing function of the natural form, several features of the Bohr atom may be pointed out. One is that a "free" electron (one not "bound" within an atom) is completely controlled by its own mass and electric charge. When within an atom, however, it "obeys" Bohr's quantum rules—not falling into the nucleus or radiating when in its assigned orbit, making only its "allowed" transitions.[18] On its own, each electron would be indifferent to the particular energy state it might occupy within the atom; within the atom, according to the Pauli exclusion principle, each electron is assigned to a unique state occupied by no other. And when, in a sodium vapor lamp, sodium atoms are energized and "excited," they direct their single valence electrons to a higher energy state, funneling all the absorbed energy into them. The electrons again do not act on their own, but return to their normal energy state by emitting the yellow light characteristic of a sodium lamp. All of these changes can be visualized in the Bohr model, and even though it fails to capture the precise reality that is the sodium atom, it does furnish an analogous insight into how form functions as a stabilizing factor in an inorganic substance.

Another view of the specific nature is provided by the element chlorine and the way it combines with sodium to form sodium chloride or common salt.[19] Identified as an element only shortly after sodium, in its natural state chlorine is a greenish-yellow gas now classified as a member of the halogen group. It is toxic or poisonous and can cause constriction of the chest, suffocation, and severe damage to the respiratory system; it has the dubious distinction of being the first gas used in chemical warfare. It also has more humane uses: it serves as a germicide and disinfectant, is a good bleaching agent, and is widely used in industry. Like sodium it can be modeled by the Bohr atom, and then it is pictured with a nucleus containing seventeen protons and eighteen or twenty neutrons, surrounded by seventeen electrons (two in the inner most shell, eight in the surrounding shell, and seven in the outermost). Since it requires only one electron to complete its outermost shell, it combines easily with alkali metals that can supply its deficit with its one valence electron: this explains why it has an affinity for sodium and joins with it readily to form common salt.

18. If the electron were "free" and orbiting the nucleus, it would emit electromagnetic waves, gradually lose energy, and ultimately fall into the nucleus. Bohr's rules specified that the electron "bound" within the atom would occupy a fixed energy level there and would absorb or emit energy only in discrete packets and only when it jumped from one orbit to another, the amount being specified by the difference of energy levels between the two orbits.

19. Chlorine was discovered by Karl Wilhelm Scheele, along with manganese and barium, in 1774; he did not identify it as an element then, however. This was not recognized until 25 years later by the discoverer of sodium, Humphry Davy.

Those who have seen and smelled chlorine gas or have observed it in liquified form know what chlorine is; if they have experimented with it extensively they know its many properties. But, as in the case of sodium, they gain a greater insight into its specific nature and its properties when they model it with the Bohr atom. In the chlorine model the electrons, protons, and neutrons, considered in themselves and apart from their presence in the chlorine atom, are the same as those in the sodium atom; the distinguishing feature of chlorine is not its material composition but rather the way its components are arranged. But again what is at issue here is not merely a structural or artificial arrangement; rather what is present is a dynamic unity that makes each component of the atom behave not as an independent nature but as a part of chlorine. The unifying or stabilizing form gives specific identity to the element and so constitutes it a natural substance in its own right. Here again what is known directly is the natural form: this is what enables us to identify chlorine and classify it among the halogen gases. Yet such a form is very well modeled by the Bohr atom, which lets us penetrate beneath the appearances, as it were, and gain an insight into the nature that makes this element be what it is and act the way it does.

Sodium and chlorine unite, as has been said, to form a very abundant chemical compound best recognized as table salt. This is usually seen in purified form as small white particles, or under the microscope as colorless but translucent cubic crystals. The taste of this substance is distinctive, and the facts that it dissolves in water, absorbs moisture from the air, and seasons and preserves food are widely known. Salt obviously has very different properties from both sodium and chlorine, and we may well wonder how these two elements can be the reagents from which it is formed. Chemists explain this again in terms of the Bohr model: single atoms of sodium and chlorine combine to form one molecule of sodium chloride. The atomic weight of the first two are 23 and 35 respectively, so salt has a molecular weight of 58. The sodium atom transfers its valence electron to the chlorine atom and fills its outermost shell; this leaves both atoms electrically charged within the molecule (and labeled "ions" on that account), the first positively and the second negatively. When a number of salt molecules are present they tend to aggregate under the influence of the resulting electrical forces and align themselves in a regular cubic lattice, the corners of which are occupied alternately

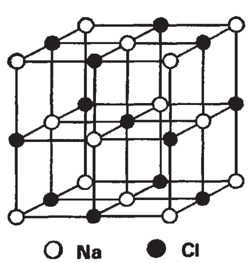

Fig. 2.4 Crystal Lattice of Salt

by sodium and chlorine ions, as diagrammed in Fig. 2.4.[20] Here the sodium ions, which carry a single negative charge, are shown as white circles and the chlorine ions, which carry a single positive charge, as black. (Note that in a cubical structure of this type each ion is surrounded by six ions of the opposite charge.) The diagram explains why at room temperatures salt appears as a cubic crystal whereas at the same temperatures its components appear as a metal and a gas respectively. The transfer of one electron from the sodium to the chlorine effects this and countless other transformations, all of which can be explained in terms of the molecular model.

Not to labor the point, we may observe that in this as in the two previous cases the model of sodium chloride is not the nature of salt nor is the model known in the same way as the nature. Far more people know what salt is than know anything about sodium and chlorine. The properties of the natural substance can be grasped quickly on the basis of ordinary experience. To say this, however, is not to devalue the type of knowledge possessed by the chemist. Like the nonchemist, he too knows very well what salt is. In fact, he possesses a much better knowledge of its nature, for he grasps its specifying form in terms of its molecular and lattice-structure models and thus has a superior insight into what makes it have the properties it does.

2.4 Activity and Reactivity

Our earlier concerns with nature as an inner dimension led to questions about agencies and finalities as these are discernible in the natural order. Such questions surface now at the level of the inorganic. Earlier we remarked that nonliving things manifest very little activity through which their natures can be known; at the same time we made a case for nature being an inner source of activity and reactivity. Our task now becomes one of delineating how intrinsic causes such as form and matter can function as efficient causes, and for what ends. Since forces and fields are used by physicists to conceptualize the agencies involved in actions and reactions, we begin our approach to the problem with them.

The particles of modern physics and the fields with which they are associated are currently discussed in terms of four major forces. The first of these is the strong force, used to explain nuclear fusion, fission, and

20. The lattice structure was discovered by Max von Laue of Germany from a study of the patterns x-rays produced when diffracted by crystals. Von Laue, who began this work in 1912, received the Nobel Prize for it in 1914.

bonding; as its name implies, it is the strongest of the forces, but it is thought to have a very short range, exerted only within the dimensions of the atom's nucleus. Next in strength is the electromagnetic force, about a hundredth of the first but exerting its influence to very great distances; it is found in explanations of electricity, magnetism, and optical phenomena generally. The third force, a thousandth of the strength of the second, is called the weak force; it seems to be involved only in phenomena of radioactive decay. Fourth and last is the force of gravity, the force of which we all have direct experience but which is extremely feeble compared to the others. The general theory of relativity explains gravitational forces in terms of the curvature of space-time, and various quantum theories attempt to explain analogous sources of the others. To date no one has succeeded in bringing all four under a single field theory, although recently an "electroweak" theory has been proposed to unify the second and the third.[21]

The weakest force of all has been longest known, yet it is probably least well understood. The force of gravity is what makes bodies fall to earth, and in a sense it is the cosmic glue that holds together the solar system and its galaxy. A piece of lead, suspended by a thread, will fall to the ground as soon as the thread is cut. What initiates its motion? One could say that cutting the thread moves it, but surely that is not the entire explanation. Even before the thread is cut, the lead was exerting a force on it, perhaps, if the piece is heavy enough, threatening to break it. In another way of looking at it, the piece of lead possesses a potential energy, a potential for movement latent within it, which is there regardless of what may be holding it above the floor—the thread or any other support, even a human hand. The moment the support is released that potential for fall is activated and what was formerly potential energy begins to be converted into the kinetic energy of motion. On the basis of this analysis it is the lead itself that initiates the motion directly, whereas whatever removes the support, the *removens prohibens*, performs only a triggering action, enabling the lead to realize its natural potential.[22] In this way of thinking, gravitational motion may be regarded as a natural motion,

21. The electroweak theory was formulated in 1967 by Steven Weinberg, Abdus Salam, and Sheldon Glashow; it received experimental confirmation in 1983 when a team of scientists at CERN (Centre Européen de Recherche Nucléaire), under the direction of Carlo Rubia, discovered particles whose existence was predicted by the theory.

22. Essentially this is how Aristotle explained the fall of bodies as a natural motion in the *Physics* (255b13–256a3): they are moved directly by whatever agent made

one that comes at least partially from within the lead, even though there may be many extrinsic factors that ultimately bear upon it.

Inorganic natures, though generally passive and inert, are all endowed with a minimal source of mechanical activity in this sense. Not only do meteorites fall to earth but trees topple over and occasionally even squirrels and cats tumble to the ground. Uniformly they then obey Newton's laws of motion (or Einstein's), regardless of their species or kind. They do so in virtue of their mass, which in turn is traceable to the elements and compounds of which they are constituted, to the atoms and molecules they contain. And since in each case the motion comes from within the object as a substantial entity, one could say that its specifying or unifying form is the basic source of its activity. But perhaps it is better to attribute that activity to something more proximate: to a potency or power that the form possesses, along the lines of the energy model. Then the actuation has a corresponding potential within the object that, when externally triggered, produces the motion that is so commonly observed.

The most radical manifestation of such a potential is seen in the mass spectrometer, an instrument devised to measure atomic weights and so detect the isotopes of the various elements. In this device, ions or charged atoms are sorted out through the use of electric and magnetic fields in such a way that their paths of travel, and thus the positions at which they impinge on a screen or photographic plate, provide a measure of their masses.[23] In effect the mass spectrometer shows graphically how the various elements tend to move and to stratify in a physical environment, with the lighter atoms ending up successively farther away from the local center of gravity. Experiments with this device show that the atoms of naturally occurring elements, although occupying the same place in the periodic table (and hence called "isotopes"), have nuclei of slightly different masses depending on the number of neutrons within them. Thus, some chlorine atoms have an atomic weight of 35 whereas others have an atomic weight of 37, the latter containing two more neutrons than the former in their nuclei (20 as opposed to 18), though both types otherwise manifest the same electrical and chemical properties.

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them heavy, and accidentally by whatever agent removes the restraint under them that is impeding their motion. See Sec. 8.2.

23. The first mass spectrometer or spectrograph was built by the English physicist Francis William Aston in 1918; he was awarded the Nobel Prize for chemistry in 1922 for his discovery of isotopes using this instrument.

Gravitational motion may be regarded as a type of reactive activity, in the sense that it is usually initiated by an external source. Reaction itself is more commonly used, however, to describe the chemical phenomena associated with the elements. Even though the Greeks thought that some elements are more active than others, they generally explained this activity in terms of warmth and wetness, as though these were the only agents that could bring it about. We now know that elements react to each other in a variety of ways, and although heat and solution are sometimes helpful as agents, the principal agent is the electric charge embodied in the electron configurations of their atoms. The electromagnetic force these electrons produce is the second in the list of four given above; in its terms practically all chemical reactions are now readily explained.

The combination of sodium with chlorine to produce salt illustrates the action of this force. Both are relatively active elements, but each requires a reagent with which to react before its activity becomes manifest. Sodium combines with chlorine because each has an electrical affinity for the other. In terms of the Bohr atom, this affinity is explained by the single valence electron in the outer shell of the sodium that is able to fill the place vacant in the outer shell of the chlorine. The reaction goes because, among other things, both electron configurations match and so produce a molecule whose constituents are bonded together in stable form.

Extending the analogy sketched above, we may say that the specifying form of both elements, sodium and chlorine, manifest this chemical activity and reactivity because they both embody an electrical potential, different from their gravitational potential and yet under proper conditions also capable of initiating a natural change, i.e., a change that proceeds from within the two reagents. Natural forms at the level of the inorganic have activities in this sense, and so they can be regarded as agents or efficient causes. Properly speaking, however, they do not act directly but rather through the powers or potentials with which the elements are equipped. A particular gravitational potential, as manifested in the atomic weight of 23, and a particular electrical potential, as modeled by the single electron in its outermost shell, serves to explain the natural activities of sodium. These also help us understand why the specific nature of this or that element is not an empirical concept, although it is readily grasped by anyone who has experience with the element. The characteristics and properties of the inorganic result from the potentials that produce them; such potentials are inferred directly, and with them, the unifying form that lies at their root. This form, or nature, is then revealed progressively and more fully as one gains greater familiarity with the activities and reactivities that originate from it.

Similar considerations enable us to understand the causal factors that produce a natural substance as opposed to an artifact. Earlier it was remarked that all chemical reactions result in products determined by nature, and this is true even though some products, such as plastics, do not occur naturally. Again, in the case of inanimate objects (as opposed, for example, to squirrels), agents and reagents usually do not replicate their own forms. Rather, the agencies that may be characterized as the potentials of those forms act on the matter with which they are associated. When they do so, generally with extrinsic factors serving as additional triggering agents, the end or final cause of the reaction is predetermined by these antecedent causal factors, namely, by matter, form, and agent. Understood in this way, nature acts for an end even in the realm of the inorganic, though its intentions are not as discernible as they are in the plant and animal world, being read only by those who have specialized knowledge of the reagents involved.

2.5 The Ultimate Substrate

Thus far attention has focused on the natural forms of the nonliving and their agencies or potentials, together with the finalities implicit within them. This still leaves for fuller consideration the matter or material substrate that underlies natural processes. We have proceeded to this point on the assumption that atoms and molecules serve as matter for chemical reactions, in the minimal sense that they provide the mass-energy that makes such reactions go. We have further assumed that electrons, protons, and neutrons, the last two located within the nucleus, function as material parts in terms of which the natures of the reagents may be modeled and so understood. These assumptions now require fuller investigation. A fruitful path is to pose the question: If chemical substances are composed of atoms and molecules, and these in turn are composed of electrons, protons, and neutrons, what more can be said about the stuff out of which the last three are made? To push the inquiry further: if subatomic particles such as these are composed of yet smaller and more "elementary" particles, is there any limit to which one can go in seeking the matter of which everything is ultimately composed? This is the question of the basic substrate of natural processes, with which we complete the analysis of inorganic nature in terms of our causal model.

Of the four fundamental forces studied by physicists, the two we have not examined thus far, the strong force and the weak force, cast light on the structure of the atomic nucleus and thus prove helpful for our purposes. Since the discovery of radioactivity at the end of the nineteenth century it has been known that certain chemical substances break down more or less spontaneously into others of lower atomic weight, and in so doing emit particles of different types.[24] Subsequent research has localized the source of this emission in the nucleus, and identified it as a process wherein the neutrons in the nucleus decompose into a proton and an electron and two other particles, all of which are thereupon ejected from the nucleus. The ejected particles are, in fact, what constitutes radioactivity. The two particles emitted along with the proton and the electron have proved extremely difficult to detect: one is now known to be the anti-neutrino, a massless and chargeless entity possessing only spin of a certain type, and the other is the W-particle, a massive particle regarded as the carrier of the weak force that holds the neutron together, discovered only recently.[25]

Radioactive phenomena aside, it has long been suspected that the nuclei of atoms must have very strong binding energies to keep their components, called nucleons, in stable configurations. In the nucleus of the sodium atom, for example, there are eleven protons all bearing positive charges and therefore repelling each other with strong electrical forces. Since the gravitational attraction of these nucleons for each other is extremely weak, indeed negligible compared to the repulsive force of the protons, the proton component of the nucleus of the sodium atom should cause it to fly apart. Because it does not do so, there must be a force of considerable magnitude that acts only within the nucleus and prevents it from disintegrating. This force is called the strong force so as to differ-

24. The first observation of natural radioactivity was made by Henri Becquerel in 1896 when he discovered radiation being given off by uranium; this was named radioactivity by Marie Curie in 1898. The radiation consists of three types of rays called alpha, beta, and gamma rays. Becquerel was the first to show that beta rays are the same as cathode rays, that is, streams of electrons. In 1900 Ernest Rutherford showed that gamma rays are like x-rays but of even shorter wavelength, and a few years later he and Hans Geiger identified alpha particles as helium atoms that have been stripped of their electrons.

25. The W-particle is one of the particles discovered in 1983 that confirmed the electro-weak theory (see note 21 above). Actually it takes two forms, the W^+ and the W^-, the first with a positive charge and the second with a negative, and is accompanied by a third particle, the Z^0 with zero charge.

entiate it both from the weak force involved in radioactive decay and from the electromagnetic and gravitational forces already discussed.

The very strength of nuclear forces requires massive equipment to break through them so as to study the structure of the nucleus. The huge particle accelerators used in high-energy physics, however, are accomplishing precisely this task. But rather than simplify the model of the nucleus, as Bohr's work simplified the model of the atom, the investigations of nuclear physicists have produced precisely the opposite result. They have led to the discovery of hundreds of new particles and antiparticles—variously classified as baryons, hadrons, mesons, hyperons, leptons, bosons, fermions, etc.—of which protons, neutrons, and electrons are merely special cases. Attempts have been made to cut through all of this complexity, but without complete success. The best that can be done, apparently, is to say that there are six ultimate states of matter, three quarks and three anti-quarks, which combine in various ways to produce the particles acted upon by the strong force. Quarks themselves cannot be isolated, since they always recombine to maintain the appearances of the known particles. Thus it is meaningless to inquire into their structure or to ask whether they are composed of more ultimate constituents. The search for a fundamental ground to all natural processes seems to end with them, or rather with a number of conservation principles on which they are based, which state the particular characteristics that will perdure throughout various nuclear reactions.[26]

The foregoing is not proposed as documenting the final stage of nuclear research. It does, however, lend strong support to a view of the substrate that goes back to Aristotle, who, as we have seen in the previous chapter, spoke of the ultimate material component as *hulē prōtē* or first matter. As Aristotle conceived it, this protomatter is not itself a subsistent formed entity but rather an unformed and indeterminate something that is at the base of all substantial change. As the basic material factor, what it contributes to the coming to be of a new substance is its potential, its ability to be determined by a specifying form to constitute an entity of a particular kind. Somewhat like the quark and the conservation principles associated with it, protomatter cannot exist by itself in isolation from a determining form. Rather it is a principle or a cause entering

26. The quark model of the nucleus was introduced by Murray Gell-Mann in 1964, following his development in 1961 of what he called "the eightfold way," a way of classifying heavy subatomic particles based on abstract mathematics whose physical explanation is formulated in the quark hypothesis.

into the constitution of a natural substance without being identifiable as a subsistent entity or substance itself.[27]

Applying this idea to the data of nuclear physics we can gain some understanding of the nature of so-called elementary particles. To the degree that these assume recognizable form and so are specifiable in terms of a characteristic mass, charge, spin, etc., they can be said to have natures that are composed of two intrinsic factors: a protomatter that in some way is conserved throughout any reactions they take part in, and a more or less transient form that accounts for whatever substantial unity they may possess. The protomatter is potential in the most basic sense and may be regarded as a radical indeterminacy at the root of all natural changes. The fact that it is conserved throughout such changes alerts us to its being also a conservation principle—not in the metrical sense of mass-energy but in the ontological sense of what underlies or grounds such a metric in the order of being. The transient form, on the other hand, is protomatter's correlative determining factor: it may be thought of as informing the protomatter and making of it a proton, neutron, electron, neutrino, etc., in much the same way as the corresponding natural forms make substantial unities of the atoms of sodium and chlorine. Unlike the forms of the elements, however, this particular determiner has no direct counterpart in sense experience.

Moreover, whereas the activities and reactivities of stable elements can be understood mainly in terms of gravitational and electromagnetic potentials, subatomic forms seem to require the additional potentials of the strong and weak forces to explain the processes in which they become involved. Possibly because of these forces the forms of subatomic entities seem not to qualify as stabilizing forms in the same way as do those of the elements. It is for this reason that we refer to them as transient forms. If nucleons, for example, become radioactive when outside the nucleus, that is, if they quickly break down to become something else, their mode of existence appears to be characterized more by transiency than by stability. And yet the fact that theirs is a fleeting existence need not deny them any substantial status whatever.

What has been said thus far applies to elementary particles as these are known to high-energy physicists, namely, as subsistent entities that have been separated out from ordinary matter, as it were, and are being

27. Precisely how Aristotle himself conceived this protomatter is much argued among classical scholars. The interpretation given here is based on the commentary of St. Thomas Aquinas on the first book of the *Physics*, thought to have been composed at Paris in the scholastic year 1268–1269.

investigated under rather abnormal conditions. One may inquire at this point whether a neutron or a neutrino that is a component of the nucleus of a stable atom has the same entitative status as a similar particle outside the nucleus. Here modeling techniques can again prove helpful. Just as the Bohr model furnishes a way of understanding how an electron functions as part of the outer structure of an atom, so other models such as the liquid-drop model and the potential barrier model have been proposed to explain how nucleons similarly function within the nucleus. And just as the behavior of the electron in the Bohr atom of sodium is dictated not by the form of electron as this might exist outside the atom but by the unifying form of sodium, so the behavior of the neutron within, say, the liquid-drop model of the nucleus is dictated not by the form of neutron as it might exist outside the atom but by the form of sodium also. In other words, the nature of sodium is such that the specifying form of that element actually informs protomatter in a distinctive way so as to structure all of its components—the nucleus and its constituents, plus the orbiting electrons—into an integral whole that responds in a way characteristic of sodium to various external influences. It is because of this unity that one can speak of an element such as radium as radioactive. The source of radium's radioactivity is indeed lodged in its nucleus, just as the source of its chemical activity is lodged in its valence electrons, but both activities are those of the specifying form of radium, which actually structures the protomatter of which this element is composed and enables it to act and react precisely as it does.

With this more sophisticated understanding of the material cause of natural substances, it is possible to return to the example of a chemical compound such as salt and identify more precisely the causal factors at work in its production. When sodium combines with chlorine to generate sodium chloride, the natural form of sodium (NF_{Na}), which informs and structures the protomatter (PM) of that element, interacts with the natural form of chlorine (NF_{Cl}), which in turn informs and structures its protomatter (PM again). In the course of the reaction the substrate (still PM) is conserved: it carries over all the potentials latent within the reagents, many of which can be assigned numerical measures. But at the end of the reaction the two previous natural forms disappear, to be replaced by a new natural form, that of salt or sodium chloride (NF_{NaCl}). This latter form gives a new unity and structure to the compound, now no longer modeled by the atoms of sodium and chlorine but rather by the molecule of sodium chloride. A new substantial unity has been achieved, with radically different properties, although something of the previous substances remains in the substrate (PM), present as before and still providing the ontological ground for all the conservation principles that are recognized as such in recent science.

From this example, and others that can easily be adduced, we may see how the essence of an inorganic substance is internally constituted both of natural form as a determining and specifying principle and of protomatter as a radically indeterminate and conserving principle. This form-matter type of composition applies equally to chemical compounds, to the elements of which they are composed, and to their elemental constituents as deeply as one may wish to penetrate into them.

2.6 Natural Generation

With these matters in hand we may now return to the causal model explained in the previous chapter to reflect at greater length on the factors involved in the generation of a natural substance, our aim now being to differentiate them more precisely from those involved in the production of an artifact. Natural generation is sometimes referred to as substantial change because it results in the coming to be of a substance, whereas the production of an artifact is seen as an accidental change because it consists in imposing a new accidental form (such as the shape of a chair) on a substance (such as oak) that remains essentially the same. To make our comparison more pointed we here change the example of the causal paradigm used in the first chapter: instead of analyzing the carpenter's production of a chair, we now analyze Michelangelo's sculpting of the statue of David from a block of marble. For natural generation we have already mentioned the formation of salt from sodium and chlorine or the decomposition of water into hydrogen and oxygen, both of which involve the generation of new substances. But an even more graphic example is provided by natural radioactivity: the production of the element lead from the radioactive breakdown of the naturally occurring element uranium. As it turns out, the case of radioactive generation lends itself better to contrasting the way agents and ends are operative in the order of nature with the way agents and ends function in the order of art. Thus we focus on it in what follows.

When Michelangelo produced his sculpture he started with a block of marble, worked on this with a chisel, and ended with the statue of David, along with a considerable number of marble chips around his studio. The principal agent (A_p) of the production was Michelangelo and the instrumental agent (A_i) was his chisel; the matter (M) on which he worked was marble; the accidental form or shape with which he started (AF_1) was somewhat indeterminate, so we shall refer to it simply as a "block"; the accidental form or shape with which he ended (AF_2) was "David"; and this also happened to be the end (E) or final cause of the sculpting process.

As contrasted with this, when the element uranium breaks down into lead, a naturally occurring substance is present at the start: this is uranium, U, whose substantial or natural form may be designated NF_1. As a natural substance it is a composite of this form and protomatter (PM), both of which may be called its nature, as shown in Fig. 1.3. At the end of the radioactive breakdown, another natural substance has replaced the uranium: this is lead, Pb, whose natural form may be designated NF_2, and it too is united with protomatter (PM) as its conservation principle.

Leaving aside for the moment the agent and end of this natural process, we may note an immediate parallel between the two types of change. In the production of the artifact, the initial accidental composition of AF_1 and M has been replaced by the different accidental composition of AF_2 and M, with the marble (M) being conserved throughout the process. This supposes, of course, that the difference between the weight of the original block and the weight of the statue is made up by that of the chips left over from the sculpting. Similarly, in the case of natural generation the initial substantial composition of NF_1 and PM has been replaced by the different substantial composition of NF_2 and PM, with the protomatter (PM) being conserved throughout the process. If we take mass-energy to be a surrogate for protomatter, as already suggested, and supply the atomic and mass numbers of the two elements, we might say that the difference between the mass-energy of ${}_{92}U^{238}$ and that of ${}_{82}Pb^{206}$, i.e., the difference between 238 and 206 or 22 mass units, has gone into the radiation products given off during the breakdown, so that mass-energy has been conserved. In this sense, then, the two processes seem quite analogous, though the first takes place in the accidental and artificial order, the second in the substantial and natural.

This analogy is diagrammed in Fig. 2.5, with the accidental change shown above and the substantial change below. If one considers the rhombic box on the lower right, one can readily see that it duplicates the inner core of Fig. 1.3 (the portion enclosed in double outline), only now stood up on one end and skewed to the right. Since the purpose of the lower part of the figure is to diagram a substantial change, the various accidents or properties surrounding the inner core in Fig. 1.3 have been left out. These assume importance, however, when questions of extrinsic causality, of agency and end, are raised in conjunction with natural generation.

Focusing now on the upper portion of the figure, we note that there is

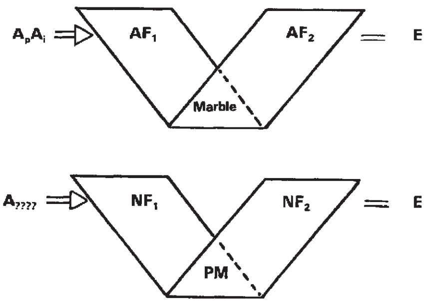

Fig. 2.5 Accidental and Substantial Change

no problem identifying the agent and the end in the production of the statue. The agent is Michelangelo (A_p) with his chisel (A_i), who works directly on the marble to hew out the form of David, which is also the end (E) of the sculpturing process. To schematize this the A's are shown with an arrow, suggesting that they are acting on the accidental form of the block of marble (AF_1), and the E is shown with an equal sign, effectively equating it with the form of David (AF_2).

When we move to the lower part of the figure we immediately sense a difficulty in identifying the agent that acts on the specific nature of uranium (NF_1) and so initiates natural radioactivity: the A in this case is shown with question marks to indicate its problematic status. The end (E) here, on the other hand, seems more readily identifiable: like the form of David, it is the substantial or natural form of lead (NF_2), a stable element that terminates what is called the uranium radioactive series.

Since NF_2 is a natural form and not an accidental or artificial form like that imposed on the marble from without, one may inquire where forms like this come from. The answer an Aristotelian philosopher such as Aquinas provides is somewhat surprising: they are not preexistent as forms, nor are they created in any way; instead, they are simply "educed" from the potency of protomatter. This is St. Thomas's teaching on the *eductio formae ex potentia materiae*.[28] It holds that all natural forms are already precontained in the potentialities of the substrate, requiring only the action of the appropriate agent to bring them forth into being. The analogy of the sculptor casts light on this explanation. We

28. Aquinas uses this expression in his *Summa theologiae*, First Part, question 90, article 2, and in his opusculum *De spiritualibus creaturis*, when juxtaposing the way in which the human soul is produced directly by God, through an act of creation, to the way in which other forms are educed from matter under the causal action of appropriate agents.

may ask where the form of David existed before it was chiseled out of the marble by Michelangelo. One answer would focus on the exemplary cause: the form existed in the mind of the sculptor. But an equally valid answer would look to the material cause, to the block of marble, and say that David's form was resident in there all along, simply waiting to be led forth, educed, liberated from the matter under the action of Michelangelo's chisel. In a proportionate way, natural forms may be said to be resident in protomatter, awaiting only the proper agent to confer on them actual existence. And if we consider mass-energy to be a metric for protomatter, corresponding to the medievals' *quantitas materiae*, we already have a measure in terms of which we can quantify many aspects of the subsequent development.

This brings us back, finally, to the agent that initiates natural radioactivity of the type seen in the breakdown of the uranium series. The answer we shall propose in the following chapter is that this particular agent is not outside the uranium the way the sculptor is outside the marble but rather is found within the uranium itself, generally in the natural forces or powers proper to all inorganic substances, and particularly in those characteristic of uranium. This is why we refer to radioactivity as natural and the process whereby the lead is produced as a natural generation. Should we further wish to inquire into the question of what there is about uranium that makes it be and act in this way, then we shall have to go back in time to the factors that produced this particular substance.

With regard to such factors, the *Handbook of Physics and Chemistry*, after noting that ${}_{92}U^{238}$ has a half-life of 4.51×10^9 years, has this to say:

> The origin of uranium, the highest member of the naturally occurring elements—except perhaps for neptunium or plutonium—is not clearly understood, although it may be presumed that uranium is a decay product of elements of higher atomic weight, which may have once been present on earth or elsewhere in the universe. These original elements may have been created as a result of a primordial "creation," known as "the big bang," in a supernova, or in some other stellar process.[29]

This explanation, it may be observed, is not very different from Aquinas's understanding of what causes the fall of an earthen body, which he regarded as a natural motion. The fall, for him, is caused proximately by earth's gravity (*gravitas*), and if one wishes to inquire further into the cause of gravity, then one must go back to earth's generator, to whatever cause it was that made earth be the way it is in the first place.

29. 66th ed., 1985–1986, p. B–40

This excursus into chemical transformations suggests a return to a point made earlier, namely, that strictly speaking there are no chemical artifacts, that all substances, inorganic as well as organic, are the work and product of nature. If this is so, then chemical formulas should be read as designating natures or natural forms that are themselves informing protomatter as their ontic, as opposed to their metric, conservation principle. Thus the equation for the radioactive process shown in the lower part of Fig. 2.5, which illustrates the transition from NF_U to NF_{Pb}, might be written:

$$_{92}U^{238} \rightarrow {}_{82}Pb^{206}$$

Alternatively, if one wishes to indicate other elements in the series and show the transitions through intermediates such as thorium (Th), protactinium (PA), and radium (Ra), that is, from NF_U to NF_{Th} to NF_{Pa} to NF_{Ra} to NF_{Pb}, one would have:

$$_{92}U^{238} \rightarrow {}_{90}Th^{234} \rightarrow {}_{91}Pa^{234} \rightarrow {}_{88}Ra^{226} \rightarrow {}_{82}Pb^{206}$$

In both expressions the subscripts represent the atomic number of the element, i.e., the number of electrons the atom contains, and the superscripts the mass number of the element, i.e., the combined number of protons and neutrons in its nucleus. These numbers then tie in the underlying substrate PM with the successive natural forms (NF's) that emerge from it in the radioactive process, for they show how various mass-energy requirements regulate the eduction of the natures that successively result. Starting with uranium, changes in both nuclear and electronic structure are necessary at each stage of the radioactive breakdown so as to satisfy the quantitative exigencies of the substrate, with the result that the specific natures of thorium, protactinium, radium, and ultimately lead, are each successively educed from within its potentiality.

Quantitative exigencies of this kind regulate not only the species or natural kinds that emerge in natural generation but also the way in which new individuals come to be. To illustrate this we may consider an example already mentioned, the chemical decomposition of water into hydrogen and oxygen. From the point of view of the specific natures involved, this may be written:

$$NF_{water} \rightarrow NF_{hydrogen} + NF_{oxygen}$$

Although here reference is made only to the NFs, the underlying supposition is that each NF is linked to PM as a substantial conservation principle throughout the decomposition. This particular reaction is written by the chemist in the well-known expression:

$$2H_2O \rightarrow 2H_2 + O_2$$

This is usually understood to mean that two molecules of water break down, under electrolytic action (the triggering agent in this case), into two diatomic molecules of hydrogen and one diatomic molecule of oxygen. The bearing of this on the problem of individuation is seen when we consider the two hydrogen molecules that result from the breakdown: each has the same nature, and yet one is distinct from the other. Whence does this differentiation arise? Assuming, from the brief discussion of Fig. 1.3 in Sec. 1.8 above, that the principle of individuation is protomatter signed with quantity, one can say that the extrinsic agent in this case (electric potential) so alters the quantitative dispositions of the protomatter underlying the water molecules that it is impossible for these to break down into one molecule each of hydrogen and oxygen. The matter of H_2O is so "signed" by its quantity that the only way mass-energy requirements can be satisfied is by the eduction from the protomatter of two hydrogen natures, each with a different but equal mass-energy, along with one oxygen nature. The individual hydrogen molecules that result are both the same, and yet they are different in the minimal sense that the extensive quantity of one is not that of the other. A biologist might say that the hydrogen molecules are twins, identical twins. But chemists do not ordinarily employ this terminology. For their science, it is sufficient to consider the specific nature apart from the individual, since in their view all hydrogen molecules are necessarily the same. The case, however, is analogous to that of natural radioactivity discussed above, where mass-energy requirements regulate nuclear and electronic readjustments at various stages in the process. In that case, of course, we focused only on the specific natures involved and did not broach the more complex problem of individuation.

2.7 Outer Space

To turn now from the realm of the very small to that of the very large, we can press our investigation of nature further by inquiring about the heavenly bodies, the vast regions of space they inhabit, and the envelope that encloses them all, the universe itself. In such an inquiry models play as important a role as they do in studying the substructure of the universe, and other models do the same for galaxies, stars, quasars, pulsars, and black holes. What is most remarkable about this extension of modeling techniques is that it has forged a surprisingly strong link between high-energy physics and astrophysics, the science of heavenly bodies. In discussions of outer space one finds as much mention of neutrons and neutrinos, for example, as in discussions of the microstructure of matter.

The major discovery that made astrophysics possible was that electromagnetic radiation can provide a clue to the composition of the sun and the stars. The optical telescope initiated this development by providing close-up views of the moon and the planets and thus enabling the structure of the solar system to be ascertained. It also revealed the existence of sunspots and led to questions about processes that might be occurring on the sun's surface and in its interior. But two other inventions have turned out to be of more fundamental importance. The first is the spectroscope, which made possible a determination of the elemental composition of the sun on the basis of the radiation it absorbed and emitted, completely analogous to the radiation absorbed and emitted by elements on earth.[30] The second is the radio telescope, which revealed radiation coming to earth from the nonvisible portion of the electromagnetic spectrum and encouraged the search for radio sources in the heavens where objects had never been seen with the human eye.[31]

For purposes of this study it is not necessary to document all of these advances. What seems important to note is that the sun is now known to be a star of a particular type, and that it is part of a large collection of stars known as a galaxy, most of which are seen from the earth as the Milky Way. The galaxy of which the sun is a part is not unique; other "island universes," as they have been called, have been identified. These likewise can be divided into types, and all seem to be receding from each other at great speed. Moreover, not all stars are single stars like the sun; some are binary or multiple, parts or groups held together by gravitational attraction; yet others are joined together in densely packed clus-

30. The first use of the spectroscope for the chemical analysis of metals placed in flame was made by Gustav Kirchhoff and Robert Bunsen in 1859; they also experimented with it to study the chemical structure of the sun. Kirchhoff detected sodium in the sun's atmosphere in 1861.

31. Radio astronomy had its beginning in 1931 with the experiments of Karl Jansky using an improvised aerial; by 1933 he had established that radio emission comes from the Milky Way. The first radio telescope proper was built by Grote Reber in 1937; through its use he produced the first radio map of the universe in 1942, the same year in which radio emission from the sun was detected by M. H. Hey and his colleagues. Beginning in the 1960s interferometry techniques were used with two or more radio telescopes to obtain results far superior to those attainable with a single large instrument.

ters, which in turn are sufficiently diversified to be classified into types. Apart from galaxies, clusters, and stars, a smaller number of "quasi-stellar objects," or quasars, are also known to exist; these have the optical appearance of stars and are sometimes radio sources, but apparently they are very bright and are receding from earth at speeds far greater than those of the galaxies.

Such a diversity of heavenly bodies is difficult enough to take into account, but the problems of cosmology, which deals with the structure of the universe, are matched by those of cosmogony, which deals with its origin and evolution. The recession of galaxies leads one spontaneously to think that at one time all galaxies were in close proximity, and thus to conceive the universe as expanding, being propelled outward perhaps after some initial "Big Bang."[32] Studies of star types have suggested an evolutionary sequence of star development according to which most stars start out, like the sun, as luminous bodies, consisting largely of hydrogen, which subsequently obtain their energy by converting that element into helium within their cores. When sufficient helium has been built up by this method the core contracts and heats up under the influence of gravity, whereas the outer layers expand and cool greatly, resulting in a remarkable increase in the star's size—to diameters tens to hundreds of times larger than the sun's—bringing the star to the "red giant" stage. Finally, when most of the energy of the star has been consumed, it contracts drastically, retaining a mass about that of the sun but compressed into the size of a planet, while maintaining a hot surface temperature, on which account it is called a "white dwarf."[33]

Depending on the size and constituents of its initial mass, a star may further have alternate fates. It may explode as a nova or supernova at the giant stage; it may continue cooling indefinitely as a dwarf; or it may compress beyond the dwarf stage to form a neutron star, an object perhaps several miles in diamenter but with matter as dense as that found in

32. The Dutch astronomer Willem de Sitter proposed in 1917, on the basis of Einstein's theory of general relativity, that the universe must be expanding; his model was improved upon by the Russian mathematician Alexander Friedmann in 1922. Using their results, the Belgian priest Georges Lemaître suggested in 1927 that the universe had started by the explosion of a "primeval atom," an event that has since become known as the "Big Bang."

33. The first "white dwarf" was detected as a companion to the star Sirius in 1841 by Friedrich Bessel, although he did not recognize it as such. The temperature of the companion star was measured by W. S. Adams in 1915 and found to be 2000°C hotter than the sun. Much of the physics of white dwarfs was worked out in 1931 by the Indian astronomer Subrahmanyan Chandrasekhar.

the atomic nucleus. The existence of neutron stars has apparently been confirmed by the recent discovery of pulsars, i.e., stellar objects that emit energy in regular pulses but at very short intervals, of the order of magnitude of a second. The emission of radiation is believed to be caused by the rotation of the source, and at such brief intervals that only a very small object could rotate fast enough, suggesting that the object itself is a neutron star. And then there is the possibility, given proper conditions, that complete gravitational collapse will set in, causing a neutron star to contract to a state so dense that not even radiation can escape from it. In this case it becomes a "black hole," a point in space that by definition can never be seen and is only observable indirectly through effects it may have on neighboring objects.[34]

So spectacular are these advances, coupled with those of space exploration, that they excite the imagination with the prospect of providing detailed knowledge of astronomical natures in the near future. They are especially helpful for showing how modeling techniques enable us to go from things near at hand to a knowledge of objects at the limits of the universe. But the very way in which we do this should remind us that the natures we really know are those we grasp directly through their sensible appearances and manifestations: hydrogen, helium, the various elements of the periodic table, their more common compounds. Whether a neutron or a neutrino considered by itself even possesses a nature thus poses a serious problem. The difficulty is exacerbated when one discusses pulsars and neutron stars, perhaps without realizing that the main language in terms of which the discussion must be carried on is that of neutrons, neutrinos, and like entities. To remark on this is not to depreciate the role of research in astrophysics. But for all its worth such research is practically at two removes from the world of nature as we perceive it: if high-energy physics stands at one remove from that world, astrophysics requires yet another remove to attain understanding of its proper subject.

Yet the study of outer space can make an important, if indirect, contribution to the definition of nature we have been pursuing. This relates to the concept of violence, a concept frequently set in opposition to that of nature. For Aristotle a violent motion is one imposed on something from without and contrary to its nature, whereas a natural motion, as we have seen, is one that originates from within and is in accordance with

34. The expression "black hole" was coined by the American physicist John Archibald Wheeler to describe an object so massive that nothing, not even light, can escape its gravitational attraction. J. Robert Oppenheimer calculated the basic properties of such an object in 1939.

that nature.[35] In most of the investigations of nuclear physics it would seem that results are achieved largely by doing violence to the subjects being studied. An atom smasher does what its name suggests: it destroys the entity it purports to study. If that is the case, how can one know that the constituents investigators allege are really *within* the atom? Are they not as much the result of artifice as of nature's manifestation? The question is difficult to answer, but a helpful reply may be the following. Researchers who make use of a cyclotron or linear accelerator in their investigations are actually exposing the materials they are studying to conditions that are violent compared to the normal ambience on earth, but that would not necessarily be violent in other parts of the universe. Just as "nature red in tooth and claw" portrays the ecological ambience in which many organic species live, so the high-energy environment duplicates that in which many elements and their components come into being and pass away. Despite their being artificially produced in the laboratory, therefore, these conditions can be found in nature and on this account prove helpful for investigating natures in the realm of the inorganic.

A similar observation may be made in connection with the "Big-Bang" model of the expanding universe. An explosion is usually thought of as a violent event, and if galaxies are receding from each other, such recession would seem to oppose the natural gravitational tendency of matter to aggregate. But just as violence may take on various meanings in different local contexts, it may be capable of a variety of interpretations in different temporal contexts. Moreover, the force of gravity is not the only natural force known to man. Forces operative in the interior of the nucleus apparently stabilize natures, and in this sense may be regarded as natural too. Questions of origins are extremely difficult to answer, particularly when the origin is so remote in time and involves spatial dimensions so different from those we experience directly in the present day. Yet our very meaning of nature is grounded in such experience, and it would be unwise to reject that meaning on the basis of hypothetical situations, fascinating to conjecture in their own right, but about which little is known with certitude at the present time.

2.8 States of Matter

The question whether a star possesses a nature is somewhat similar to whether a neutrino does so: both raise difficulties about the protomatter involved in their structure and whether or not a specifying or

35. See the beginning of Chap. 1, above.

unifying form can account for their properties. These difficulties are akin to those that arise when discussing the states of matter as ordinarily perceived. A few remarks concerning such states will enable us to rejoin concerns earlier discussed and so complete our treatment of inanimate natures.

Usually it is quite easy to identify a natural substance in the sphere of the living: one speaks of a chipmunk or an oak, and then both the nature and the individual instantiating it are readily recognized and understood. Not so in the sphere of the nonliving. Water is a good case in point: we know its chemical formula, H_2O, and this we can use to model its nature. But depending on conditions of temperature and pressure we know that this nature can exist either as a vapor (i.e., a gas), or as a liquid, or as ice in the solid state. Confronted with a crystal of ice, it may make sense to ask whether it is one or many, but that question would not make sense if applied to steam or to a large body of water. Specific identities are relatively easy to establish: most scientists would say that precisely the same nature or substance, say, water, is found in the gaseous, liquid, or solid phase. A change from one to the other would not be a substantial change but only one of accidental properties. But numerical identities offer more difficulty. A gas tends to fill a container in which it is put, and a liquid assumes the shape of the container to the extent its volume permits; otherwise fluids manifest little individual unity in their ways of acting.

Related to this question of numerical identity is one concerning mixtures of chemical reagents and the ways in which these may be distinguished from true chemical compounds. In the solid state an aggregate of salt crystals and iron filings is simple enough to recognize as an accidental unity and not as a separate substance distinct from iron and salt. When salt dissolves in water to form a saline solution, however, one is hard put to know the extent to which both the salt and the water preserve their substantial identities. In the gaseous phase the problem is similar: had investigators been able to discern that air is not a substance but is actually a mixture of several different substances, chemistry would not have languished as a discipline for so many centuries. And now that more esoteric states of matter are being investigated, such as the plasma state—one in which an ionized gas contains about equal numbers of positive ions and electrons—questions relating to its specific and numerical unities have become almost meaningless.

Of the heavenly bodies, some, such as asteroids and planets (including earth), are mainly solids, whereas stars like our sun are principally hot gases. Earth itself is a mixture or aggregate of many different elements and compounds, held together by the force of gravity. Similarly the sun is a mixture of hydrogen and helium in the gaseous state; since it seems to be a representative star, it can serve as a model in terms of which we try to understand other stars in our galaxy and throughout the universe. The unity of a star would seem to be analogous to the unity of the earth: largely a mass of different substances held together by natural forces of one type or another. And if the evolutionary model of stellar development is correct, a star can have a history even though it has not a single nature like an oak or a chipmunk. Yet there is no unifying or specifying form guiding that history toward some perfective state as in the case of these organisms. The protomatter that is distributed throughout the star's bulk would seem to be informed by a variety of elementary forms that themselves are replaced by others, as the various potentials latent within the substrate are actualized, until the mass-energy of the star is exhausted and it ceases to exist as such. Perhaps its final state would be that of a homogeneous cinder-like substance, and then all the aeons of activity could be said to terminate in one or more unifying forms, generated by the forces of nature, and yet not themselves the goal of a natural generative process.

The most perfect state in the realm of the inorganic would seem to be, not the star or the star-like object—which, like the elementary particle is somewhat transient in its being—but rather the crystalline solid. In the crystalline state, chemical elements and compounds reach the maximum degree of stability and provide the best examples of their respective properties now available. Strong forces bind atoms and molecules together in all solids and thus confer rigidity and mechanical strength on them. These forces are also present in crystals and metals, where they are further enhanced by the fact that the atoms and molecules are arranged in a most compact and regularly repeating order throughout the entire sample. Such arrangements can be modeled by lattice structures of the type shown in Fig. 2.4, and the investigation of such structures has revolutionized the study of the solid state during the past few decades.

Previous discussion of atomic and molecular models has focused attention on the energy levels that electrons occupy within the natural minima of various elements and compounds. The Pauli exclusion principle has likewise been mentioned as stating that, within a particular atom or molecule, no two electrons can occupy precisely the same energy state. This principle, moreover, has been cited as the kind of evidence that would induce one to believe that there is a specific nature in the individual atom or molecule making of it a substantial unity and not a mere aggregate of disparate components. Now the surprising discovery has been made that in regularly ordered lattices of atoms and molecules the electron configurations likewise "obey" the Pauli exclusion principle. The energy states electrons can assume within such lattices are peculiar to the various elements and compounds, making of some of them, e.g., the metallic solids, good conductors of electricity, and of others, the so-called molecular solids, poor conductors of electricity. Intermediate between these two groups there are now known to be elements such as germanium and silicon, called semiconductors, which permit only a small flow of electrons but in ways that can be controlled with unbelievable precision. Research into these substances has led to the development of transistors and silicon chips and to the remarkable revolution recently effected through their use within the electronics industry.[36]

The industrial application is not of immediate interest here, although its use in computers is important for the modeling of mind. What is of interest is that the techniques of lattice modeling and of quantum physics to explain conductivity, superconductivity, etc., hint at the existence of natural or specifying forms in the realm of the inorganic that energize protomatter and so account for these remarkable solid-state properties. Such forms do not manifest the complexity of function found in the universe of plants and animals, since their powers are restricted to the four basic forces mentioned earlier in this chapter. But the actualization of these potentials in the production of beautiful crystals attests to the goals nature is able to achieve even at the level of the nonliving. Small wonder that precious gems have been so highly regarded by mankind over the centuries, or that silicon chips are now playing such an important role in the study of human intelligence.

2.9 Models of Inanimate Substance

With this all the materials are at hand for constructing a synthetic model of inanimate substances that will incorporate most of the features discussed in this and the previous chapter. The model is not an iconic model but rather what has been referred to in the previous chapter as a powers model. As such it offers a schematic way of representing the

36. By 1948 William Shockley, working at Bell Laboratories and aided by theoretical physicists John Bardeen and William Brattain, had produced the first transistor. This made use of the fact that impurities in a crystal could be adjusted to produce an excess of electrons in one region and a deficit in another. The flow of electrons from one region to the other could then be used to simulate the operation of a vacuum tube, but without requiring heat and occupying only a minimal amount of space. Subsequent developments have led to the silicon chip and its extensive use in the computer industry.

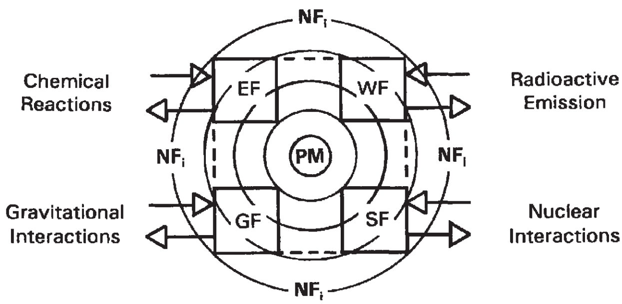

Fig. 2.6 A Powers Model of an Inorganic Nature

powers that are characteristic of an inanimate nature and that also will be useful for understanding living organisms. It thus identifies the powers that serve to explain the activities and reactivities found in the inorganic world, and then uses these to diagram how protomatter (PM) and natural form (NF) function as internal principles and so are basic for fleshing out the definition of nature at this level of being.

Figure 2.6 shows the powers model for an inorganic nature. It builds on the basic diagram presented at the end of the first chapter (Fig. 1.3), only now with the protomatter and the natural form schematized somewhat differently. Additionally, all of the accidents or properties, with the exception of the powers characteristic of inorganic substances, have been deleted from the diagram so as to emphasize the importance of such powers for understanding natures in the realm of the inorganic.

In this figure the protomatter (PM) is shown in the center, and the natural form (NF$_i$, with the subscript "i" meaning inorganic) as a series of concentric circles surrounding it. Arranged symmetrically around the center are four boxes wherein the powers that are operative in nonliving substances are diagrammed as the four forces studied in modern physics. These are, in order of decreasing strength, the strong force (SF), the electromagnetic force (EF), the weak force (WF), and the gravitational force (GF). Each of these can be correlated with an activity or reactivity that is seen in such substances. Most of the phenomena of classical mechanics, for example, can be explained in terms of the gravitational force associated with the mass of bodies. Similarly, chemical reactions can be explained in terms of the electromagnetic forces associated with electrons and ions that cause elements and compounds to enter into combination or to break down into various components. Again, to explain some types of radioactive emission it is necessary to invoke the weak force. At a more fundamental level still, nuclear reactions generally can be explained in terms of the strong force that binds nucleons together.

Inanimate substances with which we ordinarily come in contact, solids and liquids mainly, are characterized by all four forces or powers. In daily experience we notice only gravitational effects, but with some observation and experimentation we can become acquainted with chemical changes and the agencies that produce them. More sophisticated equipment is needed to gain knowledge of radioactive emission and nuclear interactions, but the powers to produce them are present in all sensible substances and thus should be regarded as part of their natures. For most of the changes we experience, a single force suffices for their accounting. When discussing nuclear processes and conditions in the interior of stars, we may need to invoke several forces, but these are not the everyday manifestations of nature with which we are mainly concerned in this study.

The four forces or powers give a generic understanding of nonliving substance but they do not provide information at a specific level. To move to this stage we must return to the essential components of substance itself, protomatter and specifying form. These are more difficult to conceptualize than the four forces and the activities associated with them. Figure 2.6 aims to assist in their understanding by showing protomatter (PM) as a central point and the inorganic natural form (NF_I) as a series of concentric circles radiating from the center and overlaying the various powers. The effect that is sought is to have specifying form appear as a type of field, coextensive with the substance of which it is the form and energizing the powers that are characteristic of it. Protomatter, on the other hand, is presented only as a point, so as to emphasize its basic indeterminacy and the way in which it is bereft of all determination or form, including even quantitative extension. Its essential characteristic is that it is a conservation principle, a substrate that perdures during changes of every type, even of the most basic kind.[37]

The specifying or substancing form, as its name indicates, is the determining factor that explains why an individual substance pertains to a

37. Activities in the inorganic realm are less noticeable than those in the domain of the living. A better idea of natural form as an energizing field and its relationship to protomatter as a conservation principle is thus conveyed by a study of the powers models of plant, animal, and human natures, as explained below in Sec. 3.4 (Fig. 3.5), Secs. 3.6 and 3.7 (Fig. 3.10), and Sec. 5.1 (Fig. 5.1) respectively. These models are also helpful for showing how the powers of the inorganic are integrated into, and serve the needs of, organic substances.

natural kind or species. It is the unifying principle that makes salt, or water, or sodium the kind of substance it is; it also serves to explain the distinctive properties or characteristics the substance manifests. To understand this, one should have recourse to the iconic models already discussed: the Bohr atom generally, the atom of sodium, the lattice structure of a crystal. The analogy of a field conveys some idea of how the components of such models are structured as they are and then regulated in their interplays and interactions. The form thus functions as an integrating factor that confers a unity and identity on otherwise disparate parts. As such, it is intelligible and the means whereby inorganic substance is known. It is not grasped directly, however, but only through the sense experiences, activities, and reactivities it sustains and directs. These phenomenal manifestations are what awaken our minds to the diverse powers and forces found in inanimate substances, and thus to the specific natures that activate such potentials and make them the substances they actually are.

Unlike form, protomatter is not intelligible in itself and can be known only through form as its correlative principle. Whereas powers or forces have sufficient determination to be differentiated from each other, protomatter is so lacking in specificity as to be graspable only as mere potentiality. We see it best on the analogy of matter and form in an artifact, as explained in Chap. 1. Just as wood is the matter that is given unity and specificity by the artificial form of chair, so protomatter is given unity and specificity by the natural form of helium, sodium, or salt. As merely potential it is undifferentiated and unspecified in itself. But the more we probe into the substructure of matter, the more we approach this basic substrate or matrix that underlies changes and so gain some understanding of protomatter itself.

2.10 Planet Earth

Of all heavenly bodies, planets are the most known to us, not surprisingly from the fact that we live on a planet and are daily in contact with it—Mother Earth. In a very real sense earth is the mother or matrix that supplies for all our needs: we are dependent on it as our basic home, the source of the air we breathe and the water we drink, the provider of plant and animal life from which we derive our sustenance. Gazing into the starry sky gives us an appreciation of nature, as already noted, but it is our experience with earth's surface and the creatures inhabiting it that enables us to understand natures in a very special way. Mountains and lakes, rivers and oceans, volcanoes and icebergs all impress us with their beauty; earthquakes, hurricanes, and floods daunt us with their power and terrorize us with the destruction they sometimes let loose. The ancients tried to explain all this in terms of concentric spheres of earth, water, and air; we speak instead of the geosphere, the hydrosphere, and the atmosphere, and our sciences of geology, oceanography, and meteorology attempt to explain the phenomena characteristic of each. In so doing, these sciences make liberal use of physics and chemistry, with the reasonable expectation that their knowledge of inorganic nature and its four basic forces will ultimately suffice to lay bare all of earth's secrets.

How and why earth came into being with its aqueous and gaseous envelope is a fascinating problem that as yet has no definitive solution. In a similar category lies the question whether earth is unique, or whether throughout the vast expanse of the universe there are many earths, each with an abundance of inorganic and organic forms that match those found in our own. The fact that the sun is a star and that there are billions of like stars in the heavens prompts speculation that there must be countless solar systems, some numbering among their planets bodies with geospheres, hydrospheres, and atmospheres analogous to earth's. There is little direct evidence to confirm this at present, but that of course does not eliminate the possibility. Meanwhile, fancies about extraterrestrial creatures, intelligences, even civilizations are a ripe field for science fiction and for the cinematic productions they continue to inspire.

Hard science is not primarily concerned with such speculation but rather with analyzing the vast amount of data available close at hand, here on earth, so as to gain deeper understanding of the workings of terrestrial nature. Meteorology in particular has made tremendous strides as a discipline, with the advent of weather satellites and the use of complex modeling techniques to forecast atmospheric conditions throughout the globe. With regard to earth itself, a number of models have been proposed to account for its structure and for the forces that shape its surface. Within recent years the plate tectonic model has given new insight into the formation of continents as well as the rise and fall of mountain ranges.[38] Other models picture the earth's gravitational field and its vari-

38. The plate tectonic model grew out of the ideas of Alfred Wegener, a German meteorologist who proposed in 1912 that continents drift apart, and those of the American Harry Hess, who augmented Wegener's notion in 1960 with his theory of sea-floor spreading. Combining the two, geologists now speculate that the crust of Earth is broken into a number of large plates that move through a semiliquid region of Earth just below the crust itself. Mountain ranges form in regions where the plates bump into each other. Most earthquakes and volcanoes also occur at the plate boundaries.

ations, the magnetic and electrical properties it manifests, and thermal effects throughout its bulk. Little is known about its core or innermost regions, but even here research is proceeding on the basis of seismic waves, earthquake analysis, and knowledge of geochemical factors. Obviously, most is known about the earth's crust, where the sciences of mineralogy and crystallography reveal the marvels of the higher inanimate forms mentioned earlier in this chapter. Recorded in the various strata of that crust are also the most salient events of earth's history. Fossils are of particular interest, for they provide evidence of living forms no longer present on the earth's surface that can be integrated with those still extant to flesh out a likely picture of organic evolution.

As fascinating as paleontology can be, the obvious fact is that we learn more about organic natures from a study of organisms now accessible to us than we do from conjecturing about those of the remote past. The atmosphere, the oceans, and every part of the earth's surface are inhabited by all kinds of plant and animal life. An examination of the processes they undergo can shed light on many additional workings of nature as well as on the mystery of life itself.

3 Plant and Animal Natures

Unlike the inanimate world, the world of plants and animals offers a rich abundance of natural kinds that have been recognized as such for millenia. Students of nature have not been content merely to distinguish the living from the nonliving or plants from animals, but have worked seriously at differentiating each type from every other. In this project the sense of "natural kind" is that it designates a class of things alike in all their essential characteristics, that is, sharing a common nature though differing in individual traits.

The abundance of detail available in the study of organisms makes it no simple matter to separate the incidental from the essential in this way. As already remarked, physicists and chemists do not have to address the problem of individuation in their subject matter. They simply assume that all electrons or water molecules are the same, and they work at distinguishing electrons from protons or neutrinos, or water from hydrogen peroxide or carbon tetrachloride. Even when considering a protein molecule as complex in structure as DNA, chemists tend to regard it as replicating itself to produce an exact facsimile of the original, different only in its location in space and time, identical in every other respect.[1] The naturalist studying butterflies or sparrows and attempting to classify them into kinds cannot proceed so simply. A difference in coloring or in organ formation might be incidental in the way that negroes or caucasians and pug-nosed or aquiline are merely accidental variations within humankind, but it might be an indication that one is dealing with specimens that are not only individually different but pertain to species that are quite diverse.

1. Recent studies have shown that this is not always the case. See John Rennie, "DNA's New Twists," *Scientific American* 266.3 (1993), 122–132.

3.1 Species of Organisms

One of the earliest tests to differentiate species or natural kinds is based on the ability of organisms to reproduce, i.e., to produce another individual similar in kind. In types that procreate sexually, individuals that can interbreed and produce normal offspring are regarded as pertaining to the same species even though they differ widely in individual characteristics.[2] In such cases nature gives evidence of the specifying forms it is able to produce. These are latent within the individual, as it were, and emerge in another individual under the influence of the proper actuating causes. The workings of nature in such reproductive processes are analogous to those by which chemical compounds are built up from their elemental constituents: even though human agents may bring together the reagents or the genetic materials, it is nature that determines what is to result and in this sense is the specifier of the natural kind.

Here is not the place to address the complex problems of taxonomy and biological classification, on which botanists and zoologists have worked for centuries.[3] Suffice it to note that in both the plant and animal kingdoms it has been found necessary to introduce higher groupings under which species can be included. These are customarily listed, in decreasing order of generalization, as kingdom, phylum, class, order, family, genus, and species. Even these rankings, however, are not sufficient to take account of the wide diversity of living forms, and thus prefixes such as sub-, super-, and infra- are frequently appended to them. For example, if a class is not sufficient to indicate a diversity within a phylum, one may introduce a superclass above it, and then a subclass below it, and even an infraclass below that. Additional rankings are sometimes inserted, such as cohort or tribe, if the resulting groupings are not sufficient to encompass all the known types. What is amazing, however, is that proceeding in this way biologists not only can classify existing

2. The Biological Species Concept, formulated in 1942 by the Harvard biologist Ernst Mayr, has been generally accepted by zoologists and taxonomists. It states that most species occupy distinct ecological niches and that the basic criterion for discerning whether organisms belong to a species is whether or not they interbreed.

3. The modern system of classification of living organisms, which uses a system of binary notation for naming species, was inaugurated by Carolus Linnaeus in his *Systema naturae*, published in 1735. He completed the work with the publication of his *Systema plantarum*, which appeared in 1753. For an account of the *Systema naturae* and its publishing history, see Derek Gjersten, *The Classics of Science: A Study of Twelve Enduring Scientific Works*. New York: Lilian Barber Press, Inc., 1984, pp. 221–258.

species but can also locate newly discovered specimens within the hierarchy and label them in such a way as to differentiate them from their neighbors.

The great chain of being that results from such classification may be regarded as simply a hierarchical arrangement that manifests the wonderful diversity of living types to be found in nature, from lowest to highest. But, with the advent of Darwin and successive modifications of his evolutionary theory,[4] a deeper significance is becoming manifest in classificatory schemes. They seem now to provide more than a static picture of the order of nature as we presently conceive it; they describe also a developmental framework in which species no longer extant but somehow preserved in the paleographical record can be located with respect to those now flourishing. The ideal that this discovery suggests is that natural classifications result not merely from the work of taxonomists but from the succession of types that originate within nature by an evolutionary process. If this is the case, then one day it will be possible to locate all naturally occurring species not merely within a hierarchy but also as branches of a phylogenetic tree—thus situating them in their dynamic and evolving relationships.

Yet the separation of species within the organic realm is not something that can be mathematically determined and categorized along rigidly dichotomous lines. Just as the necessity of nature is not absolute, so the ways in which types are differentiated are not absolute either. Even the difference between plants and animals allows for fuzziness between their respective kingdoms. Plants, for example, are usually characterized by the fact that they obtain nutrients through a process of photosynthesis, using solar energy and chlorophyll to convert water, carbon dioxide, and minerals into food they can use. Their component cells contain cellulose in their walls and on this account are more or less rigid, lacking the flexibility found in the animal kingdom. They grow by a process that is somewhat unlimited, lack organs of locomotion, generally being rooted in one place, and have no sensory or nervous systems such as are found in animals. Yet there are exceptions: some plants are not green, lacking chlorophyll, and so obtain their food from other living plants or from dead organic matter. Some animals, on the other hand,

4. The first edition of Charles Darwin's classic, bearing the title *On the origin of species by means of natural selection or the preservation of favoured races in the struggle for life*, appeared on November 24, 1859. Six editions were published in Darwin's lifetime, the last in 1872. Over 150 editions in all have been published in Britain and the U.S. For a detailed account of the book and a history of its publication, see Gjersten, *The Classics of Science*, pp. 316–353.

lack mobility and remain in one place most of their lives; others such as coral have processes of essentially unlimited growth that put them closer to plants in this respect.

Such anomalies were known to the ancients, but with the perfection of the microscope and consequent research into micro-organisms they became more serious.[5] Unlike the higher forms of life containing millions of cells, unicellular organisms perform many functions within a single cell and do so in ways that make them difficult to classify along plant and animal lines. Bacteria and viruses present analogous problems:[6] the former do not necessarily use oxygen in their life processes, sometimes employing sulphur or iron instead, whereas the latter have no self-sufficient life functions but remain always parasitic on other organisms. Rather than attempt to fit all of these types into the two kingdoms known to the Greeks, modern biologists add at least two separate kingdoms: procaryota, to take care of bacteria and viruses, which have no clearly defined nucleus in their cells for hereditary material; and protista, those with a nucleus enclosing genetic determiners, to take care of unicellular plants, animals, and intermediate forms. Fungi of various types are sometimes assimilated to the protista, sometimes put into a separate kingdom of their own on the basis that otherwise they resist proper classification. The two highest kingdoms are then called metaphyta and metazoa, respectively, the plants and animals of ordinary experience.

In many ways progress in biological classification has unveiled a substructure in the organic realm analogous to that known to physicists and chemists from their work with the inorganic. Minerals were classified for centuries before elements and compounds were recognized and the microstates of matter—molecules, atoms, and subatomic particles—successfully identified. But once discovered, the world of elementary particles has given a remarkable insight into the protomatter that under-

5. Hans Lippershey is commonly regarded as having invented the compound microscope in 1609, although Zacharias Janssen may have done so independently as early as 1590. Anton van Leeuwenhoek informed the Royal Society in England of his discoveries with the simple microscope in 1673; in 1677 he discovered protozoa through its use, and in 1683, bacteria.

6. Despite Leeuwenhoek's observations, the first systematic treatment of bacteria was not published until 1872, when Ferdinand Cohn divided them into genera and species. Viruses were first shown to exist in 1892 by the Russian biologist Dmitri Ivanovsky. It was not until the 1930s, however, that the tobacco mosaic virus was isolated. In the 1940s the introduction of the electron microscope made it possible to photograph viruses directly.

lies all natural change and the basic potentials that make such change possible. Similarly, the wide and continuous range of development that has enabled living forms to reach the state of complexity they have in observable specimens would never have been appreciated without the study of microorganisms. Such research, plus the insights provided by molecular biology, genetics, and evolutionary theory, furnishes a complementary insight into the specifying forms that come to determine protomatter and produce, along with it, the endless variety of species in the universe of the living.

The problem of speciation is still not completely solved, but locating it in an evolutionary context offers a great advantage from the viewpoint of this study. It forces the taxonomist to work with the systematic biologist and acknowledge that species actually are natural kinds, that is, kinds that result from processes at work in nature and therefore are manifestations of nature itself. The fact that individuals vary in many ways within a kind does not invalidate the concept of specifying form; taxonomists continue to overcome the obtacles presented by accidental variation and succeed, by and large, in locating specimens within their proper class. Over and above this, moreover, the fact that individuation is so easy to observe in the domain of the animate, whereas it remains problematic in that of the inanimate, and especially at the microlevel, offers an extra bonus. It enables one to observe in countless ways how the specifying form is also a unifying form, integrating a wide variety of functions and enabling the organism to operate as a substantial unit throughout its entire life cycle.

The unity in being and operation that is found in plants and animals is easily recognized: that is why they are called organisms, for their many organs act for the good of the whole. Aristotle recognized that such organs exercise the basic powers required for life processes, which he identified with those of nutrition, growth, and reproduction. Modern biologists, studying in detail the mechanisms whereby chemicals serve the needs of organisms, have better understanding of the ways in which such powers function. Like physical scientists they employ models to gain an insight into such processes as metabolism, homeostasis, and the control of genetic factors in development and reproduction. For our purposes it may suffice to discuss only a few of these in what follows. Obviously they complement the Bohr model of the atom by furnishing insights into the modeling techniques that are becoming distinctive of the life sciences.

3.2 Metabolism and Homeostasis

The unifying function of form is seen in all vital operations, but at a fundamental level it is most manifest in metabolism, i.e., in the chemical processes whereby energy is provided to maintain life, and in the various controls that make this possible.[7] All living organisms derive their energy from sunlight: some do so directly through photosynthesis, whereas others use the products of photosynthesis as food and thus as their indirect energy source.[8] In the direct process carbon dioxide, water, and ammonia are the basic chemicals required for life; in the indirect, the various components of food—proteins, carbohydrates, and fats—serve as more complex sources. The chemical reactions such sources undergo break down the initial materials so that they can be readily synthesized into the parts of cells, enabling cells to grow, preserve their identity, and reproduce. Metabolism itself is thus the functional link between the animate and the inanimate worlds. Chemically its processes are extremely complex, and yet they are so finely controlled that, from the foods available, precisely the required amounts of energy are produced when and where they are needed within the organism.

One of the major discoveries of biochemistry is that a single compound, adenosine triphosphate (ATP), is the major carrier of chemical energy in all forms of living matter.[9] When this substance is synthesized, in exchanges known as catabolic reactions, energy is absorbed; when it is decomposed, in anabolic reactions, energy is released. ATP loses its phosphate group when it transfers its energy to other molecules, but it can be reconstituted by photosynthesis or by alternative chemical reactions in nonphotosynthetic organisms. Thus, through the functioning of this substance, metabolism can be seen to involve a network of cellular processes that bring about a continuous interchange of matter and energy between the organism and its environment.

Such processes are self-regulating in striking ways, so much so that they are suggestive of the traditional definition of life, namely, the capacity of an organism to initiate and sustain self-movement (*sui motio*)

7. The first study of metabolism was made by Sanctorius Sanctorius in his *De statica medicina* of 1614, in which he recorded measurements of changes in his own weight, pulse, and temperature.

8. Melvin Calvin, who began to use the carbon–14 isotope in the investigation of photosynthesis in 1945, was awarded the Nobel Prize in 1961 for his work on the chemistry of that process.

9. This compound was first isolated from muscle tissue by F. A. Lipmann in 1929; it was synthesized in the laboratory by A. R. Todd in 1947.

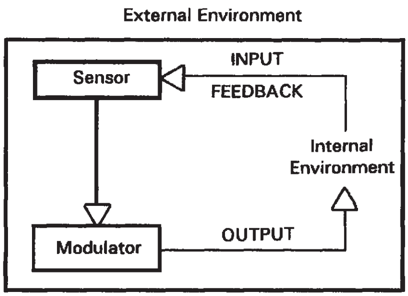

Fig. 3.1 Elements of Homeostasis

and in this sense to be self-perfecting in its ongoing processes. The basic mechanism whereby such regulation is achieved is known to biologists as homeostasis.[10] This may be defined as the regulatory process whereby living systems seek to maintain stability, that is, a state (*stasis*) that continues to be the same (*homeo*), while at the same time adjusting to conditions that are optimal for their survival. What is sought through the process is thus a type of dynamic equilibrium, dynamic because it involves more or less continuous change, equilibrium because its end result is a condition of relative uniformity.

Homeostatic processes are sufficiently similar to cybernetic devices that the latter can be used to model them.[11] Usually the basic operations for control are those of on-off switching, which determines whether or not an action occurs, or feedback, which permits an adjustment to be made within a system on a continuing basis. In the first case the switching is regulated within a predetermined range by some measuring device, whereas in the second a control mechanism induces either a positive or a negative change, whose amount is governed by some effect that is being produced within the system. Figure 3.1 illustrates the basic elements of the second type of homeostasis that would be involved in maintaining equilibrium between an external and an internal environment. Essentially it consists of a register that measures some parameter in the internal environment and a modulator or effector that is able to change that parameter in reaction to external changes. Whereas mechanical or electrical regulating devices, such as a home thermostat, are rigid and

10. The American physiologist Walter B. Cannon (b. 1871) developed a complete theory of homeostasis after World War I, although the concept was earlier advanced by Claude Bernard in his *Leçons de physiologie expérimentale* in 1855.

11. The basic concept of a cybernetic device was elaborated by Norbert Wiener in his *Cybernetics* of 1948, in which he elaborated a detailed mathematical analysis of the theory of feedback and automatic control processes.

determined in their operation, biological regulators are flexible and adaptable. The plant hormone auxin, for example, works homeostatically to regulate growth by controlling water intake and so stimulates or inhibits the rate at which the plant develops—variable over a range, yet optimal considering the environment in which the plant is placed.

Some years ago an English scientist, W. R. Ashby, developed a device of this kind to study rudimentary life processes.[12] He called it a "homeostat" because its goal was to simulate and achieve a state of homeostasis such as that found in living organisms. His device emulated an animal organism, making use of a number of electronic circuits similar to the reflex arcs in an animal's spinal cord. Out of many thousands of possible connections, the homeostat was able to find one that would lead to a condition of stability whereby it would effectively neutralize any change imposed on it from without. Curiously enough, which path it would select could not be determined short of what the inventor called "killing" the device and dissecting its "nervous system," that is, shutting off the current and tracing out the circuits it had automatically selected so as to maintain its steady state.[13] By their very nature, nervous control mechanisms of this type are found only in multicellular animals, whereas chemical controls are found in all organisms. The latter operate much more slowly than the former, and yet they are satisfactory for controlling even animal functions, such as digestion, salt-water balance, metabolism, and growth.

Homeostasis and metabolism are pervasive in the plant and animal worlds and serve to connect them with the physico-chemical realm of the inorganic. The mechanisms they employ in making this connection unfortunately escaped human detection until the early part of the twentieth century; only then, through the pioneering work of Linus Pauling and others, was the chemical bond sufficiently understood to furnish insight into the ways in which inanimate substances come to be incorporated into living matter.[14] But beginning in the late 1930s, and gaining impetus with the discovery of the double helical structure of DNA in 1953, biochemistry and genetics have grown by leaps and bounds. The

12. This is described in an article by W. Grey Walter, "An Imitation of Life," in *Automatic Control*, ed. Dennis Flanagan et al., New York: Simon and Schuster, 1955, 123–131.

13. Ibid., 125–126.

14. Linus Pauling's *The Nature of the Chemical Bond, and Structure of Molecules and Crystals* was published in 1939 and quickly became a classic on that subject. In 1954 Pauling was awarded the Nobel Prize in chemistry for his work on chemical bonds.

resulting development of molecular biology furnishes some of the best models now known for representing the mechanisms employed by nature within the organic realm.

The basic unit of life, analogous to the atom in the inanimate, is the cell[15]—a structure that in isolation is spherical but assumes other shapes when squeezed or stretched by its neighbors. All cells are now known to be basically similar, most of them less than a millionth of a centimeter in length. They consist of a bag of fluid surrounded by a permeable membrane or cell wall through which atoms and molecules pass in both directions during life processes. The atoms most important for life are those of carbon, hydrogen, nitrogen, oxygen, iron, sulphur, and phosphorus. These are usually combined into large molecules called macromolecules and consisting of tens of thousands or even hundreds of thousands of atoms. Protein molecules, made up of chemicals that contain the NH_3 group and are known as amino acids, are essential constituents of all living cells. Their mass can range anywhere from a few thousand to several million units of atomic weight. Yet a single cell of bacterium may contain five thousand different kinds of organic molecule, three thousand of which would be proteins of various types.

Compared to the cell, atomic dimensions are very small indeed, so much so that it is difficult to comprehend how atoms and molecules enter into the cell's structure. Atomic dimensions are usually measured in terms of the Angstrom unit, which is 10^{-10} meter or one ten billionth of a meter, roughly the diameter of the hydrogen atom's electron orbit in its ground state. This diameter is 10^5 or a hundred thousand times that of the proton, the nucleus of the hydrogen atom. A typical atom might have a radius between one and ten Angstrom units, with most of its volume taken up by its orbiting electrons; practically all of its mass, however, is concentrated in its nucleus, where its protons and neutrons are closely packed together under the influence of the strong force. As it turns out, for purposes of molecular biology most atoms may be treated as more or less the same size, with the outer dimensions being somewhat vaguely defined as a cloud of negative electric charge.

Atoms bond together to form molecules by sharing electrons, as described in the previous chapter, but also when urged to do so by the electromagnetic and gravitational forces likewise detailed there. Two hy-

15. The cell theory was first proposed in 1838. In that year the German biologist Matthias Schleiden recognized that cells are the fundamental components of plants. A year later his compatriot Theodor Schwann extended that work to animals and laid the foundations for cell biology.

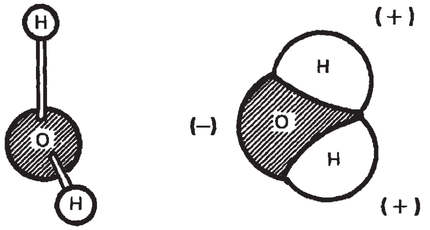

Fig. 3.2 Conventional Models of a Water Molecule

drogen atoms, for example, may combine to form the hydrogen molecule; alternatively, two hydrogen and one oxygen atom may combine to form the water molecule. Whereas the "electron cloud" around the hydrogen nucleus is spherical in shape, and that of other atoms sometimes fits spherically around the nucleus, in general this is not the case. Usually electron orbitals have a distinctive shape and orientation with respect to each other, with the result that they stick out of the atom in clearly defined and predictable directions. It is these orientations that help to explain the structures and shapes of the molecules that result when atoms of various types combine. They also serve to explain the charge clouds of the molecules that are produced, which cause them to enter into combination with other molecules or molecular groups to form the larger and larger molecules that can support life functions.

A simple example that illustrates this is the water molecule, pictured in two conventional ways in Fig. 3.2. The representation on the left, referred to as a "stick and ball" model, shows the oxygen atom as a ball joined by sticks to two smaller balls, the hydrogen atoms.[16] The sticks represent what are called "covalent bonds," that is, a pair of electrons shared between two atoms and occupying two stable orbits, one of each atom. In this way the outer shells of the two hydrogen atoms as well as that of the oxygen atom are completed. Moreover, in seeking the lowest possible energy states and thus satisfying the rules of quantum chemistry, the two hydrogen atoms align themselves in such a way that the two sticks make an angle of precisely 104.5°. Thus the water molecule assumes the form of a shallow "V," and in so doing assumes electrical properties that are peculiarly its own.

16. Explanations of this and other models of atoms will be found in John Kendrew, *The Thread of Life: An Introduction to Molecular Biology*, Cambridge, Mass.: Harvard University Press, 1967. See also John Gribbin, *In Search of the Double Helix: Quantum Physics and Life*, New York: McGraw-Hill, 1985, which has guided much of the exposition that follows.

An alternative way of modeling this molecule, and one better adapted to showing the charge distribution that results from the union of its three atoms, is shown on the right of Fig. 3.2. This is called a "space filling" model because it neglects the distances between the nuclei of the atoms and emphasizes instead the integrated structure of the electron cloud that surrounds the nuclei. The cloud itself is roughly spherical in shape, but it shows two bulges where the hydrogen atoms protrude from its surface. Because of the way the electrons of the respective atoms are shared in the chemical bonds, the side of the molecule where the hydrogen atoms are found presents itself as positively charged to neighboring molecules, whereas the opposite side presents itself as negatively charged, even though the molecule as a whole is electrically neutral. Such directional assymetries in charge distribution explain not only why water molecules align themselves in crystals to form snowflakes or ice, but also why molecules in general combine with others to form larger and larger molecules.

Textbooks in biochemistry abound with diagrams that model organic compounds in the two ways shown in Fig. 3.2. Usually the "stick and ball" model is presented in simpler fashion, showing only the structural configuration of the atoms making up the molecule and using single lines to represent the bonds between them. The "space filling" model is of course more difficult to draw, but overall it gives a better idea of the molecule it is intended to portray. A comparative picture is shown in Fig. 3.3, which presents the two models respectively of glucose ($C_6H_8O_6$), with the "space filling" model this time on the left. In it the carbon atoms are shown as black, the hydrogen atoms as white or open, and the oxygen as cross-hatched. The "stick and ball" model on the right is much simplified, with the sticks now being replaced by lines and the balls by letters that designate the respective atoms.

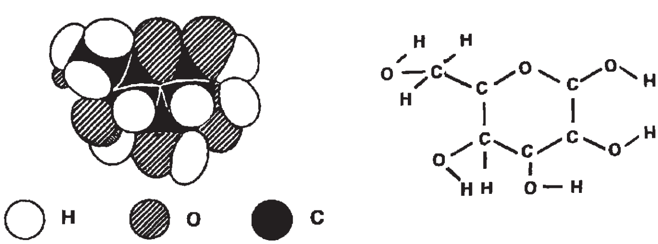

Fig. 3.3 Conventional Models of a Glucose Molecule

When one visualizes various biomolecules in the space-filling way, it becomes much easier to link together the domain of the inorganic with that of the living. The cell wall and the fluid that makes up its interior can be seen as masses of atoms and molecules, including macro-molecules of enormous size, with the fluid portions moving in closely packed swarms whose consistency is determined mainly by the attractive and repulsive forces between them. These provide the matter, the material substrate as it were, for the various life processes that go on within cells themselves and within the multicellular organisms they in turn constitute. In this way biochemistry can be put at the service of biology to explain how various organisms nourish themselves, continue to grow and develop, and finally produce other organisms similar to themselves in the reproductive process.

3.3 Development and Reproduction

The ways in which organisms, both plant and animal, develop and grow offer a striking illustration of how metabolism works in the realm of the living. The essence of growth is increase in size, and in this sense inanimate objects such as crystals can be said to grow during their formation. But crystals do not grow in the same way as plants and animals, for the process of accretion from without whereby they increase their dimensions is quite limited, and they never reproduce themselves. In living things, growth is not from without but from within, by an increase in the number and size of their constituent cells, and it always eventually includes reproduction. Moreover, whereas crystals sometimes grow randomly, organisms do not increase the size and number of their cells in random fashion. Instead they develop according to a specific plan that ultimately determines the size and shape of the particular individual. Sometimes growth is restricted to special regions within the organism; sometimes the cells engaged in growth will be widely distributed throughout the organism, with different rates of cell division and size increase being characteristic of the various parts.

As to cell division itself, this is a type of reproduction that is part of the growth process. The cellular mechanism involved is called mitosis; in it the chromosomes carrying the genetic material are first reproduced within the nucleus and then the doubled chromosomes are precisely divided between the two daughter cells.[17] Growth in animals is typically

17. The discovery of chromosomes and their role in mitosis was first reported in 1882, with the publication of *Cell Substance, Nucleus, and Cell Division* by the German biologist Walther Flemming.

effected by this process, operating in conjunction with size increases within the cells. Growth in plants differs from this in that plant cells, after dividing, generally increase their size dramatically without making continued use of the division process. The increment is brought about by the cells themselves taking up large amounts of water and storing it in cavities called vacuoles. The pressure of this water, acting on the cellulose walls of the plant cells, brings about increases in the length and breadth of the cells and ultimately of the plant itself. Also instrumental in this process is the organic substance auxin, a hormone produced in the leaves that makes its way to other parts of the plant where it controls cell elongation. It does so by acting on the rigid wall of the cell to make it more flexible; the internal pressure within the cell then forces it to become larger.

Although growth and development take place in similar ways in plants and animals, there are also significant differences. An important common element is that plants and animals share a chemical basis of inheritance in DNA and a mode of translating their genetic codes through structural units called proteins. Most plants, however, sustain growth throughout life, whereas animals grow for a determinate period to reach maturity and then cease growing. Yet even in plants the growth process, while ongoing, is not uniform and continuous; the leaves of a given species, for example, attain a specific size and then grow no larger. What determines the limits of organ size and of total body size, in both plants and in animals, is not well understood, though it seems to be traceable to common genetic factors. It is thought that the liver, for example, is able to release protein molecules into the bloodstream that limit growth of that organ. Likewise other organs may produce substances that serve to inhibit their growth, thus making use of a negative feedback mechanism in homeostatic fashion.

Another interesting developmental process is referred to as morphogenesis. This is the process whereby parts of a developing system come to acquire definite shapes or to occupy particular relative positions in space. Some morphogenesis can be explained simply in terms of the differential growth factors mentioned above, whereas some requires explanation in terms of what are called "morphogenetic fields"—masses of tissue that give no obvious indications of where various elements in the pattern will arise until they actually appear.

A yet more striking characteristic of developmental systems is their tendency to produce a normal end result in spite of injuries or abnormalities that may have affected the system in its earlier stages. Regulation likewise controls this process, and yet it is not a regulation back to some initial stable equilibrium, as in homeostasis, but rather to some future state along the time trajectory. Attaining this end state, which is not necessarily unitary but might result in a number of different organs and tissues, is referred to as homeorhesis (from *homeo*, meaning "same," and *rhesis*, meaning "a flow of words"), which translates into "maintaining the flow," that is, sustaining the movement toward the developmental goal.

Most of the growth and development that has been discussed thus far involves reproduction in the minimal sense of cell division. In single-celled organisms the division of the cell is also the reproduction of the organism, since the cell is the whole organism. Multicellular organisms require more complex processes to produce a copy or likeness of themselves; these involve first growth, that is, the enlargement of the organism by cell multiplication, then regeneration or the replacement of parts, and finally the production of offspring, which is organismic reproduction in the proper sense. The last named form of reproduction may be asexual, by some form of simple division, or sexual, by some type of conjugation of organisms.

Asexual or vegetative reproduction is typical of the plant kingdom and comes about through the development of cells specialized for this purpose, called spores. This type of reproduction can take place in a variety of ways and usually results in new plants identical in all respects to their parents. It is not universal, however, for some species of plants reproduce sexually, doing so through other types of specialized cells called gametes.[18] Sexual reproduction in plants involves a series of cellular events that employ chromosomes and their genes as well as a complex reproductive apparatus. This mode of reproduction is less determined in its operation and so leaves room for the production of plants different in some respects from their parents. In the animal kingdom sexual reproduction is more common in the higher forms, though it is not universal either, since some animals reproduce asexually—a mode that occurs only in the invertebrates. Reproductive organs, called gonads, are temporary in many lower animals, whereas in higher animals they appear as permanent organs. In the lowest forms of invertebrates the gonads are situated on or near the animal's surface; in higher animals they tend to be more deeply situated and have associated with them in-

18. The fact that plants, like animals, have two sexes was first recognized by the Venetian biologist Prospero Alpini around 1580. The male and female reproductive organs in plants were not identified until 1694, however, when the German biologist Rudolph Camerarius differentiated between them.

tricate duct systems. It is also possible for one individual to possess functional reproductive organs of both sexes; this is called hermaphroditism and is common among lower invertebrates.

The basic mechanism that lies behind all reproductive processes in plants and animals is one of molecular replication, first explained in satisfactory fashion by Francis Crick and James Watson following their research in 1953 on the structure of the DNA molecule.[19] The letters used to name the molecule come from its proper chemical designation, DeoxyriboNucleic Acid, wherein they are here shown capitalized; this is a compound of "deoxy" and "ribonucleic acid," meaning literally a nucleic acid that yields ribose ($C_5H_{10}O_5$) and from which oxygen has been removed. (Ribonucleic acid, abbreviated as RNA, itself plays an important part in the reproductive process, to be described below.) The DNA molecule assumes the form of two helical strands of nucleic acid that are intertwined, whence it is referred to as "the double helix." The strands are long threadlike molecules made up of repeating groups of structural units called nucleotides; these are joined into helical form by cross-links, bases of a particular type, which give a measure of stability to the molecule. DNA is thus a flexible macromolecule made up of structures that repeat themselves along the chain. It has been likened to a spiral staircase wherein the cross-linking bases are the steps and the strands of nucleotides are the banisters. The basic structure of a portion of the molecule is modeled in Fig. 3.4 in space-filling form, with the strands of nucleic acid shown as cross-hatched and the connecting bases as white or open. The entire molecule can be very massive, in some forms having a molecular weight of over a hundred million units of atomic mass.

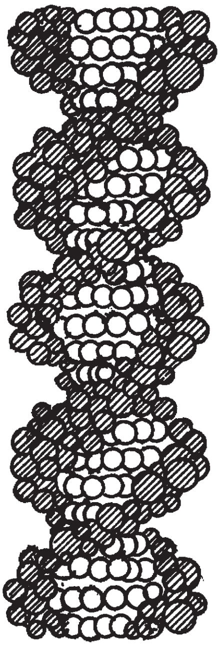

Fig. 3.4 A Space-Filling Model of the DNA molecule

On the basis of this structure it is possible to understand how the DNA molecule replicates itself. At some place along its length the two strands begin to separate and then come to be progressively unattached.

19. Much research was done on the structure of the DNA molecule by Linus Pauling, Maurice Wilkins, and Rosalind Franklin, among others, before Crick and Watson came up with the correct model, for which they were awarded the Nobel Prize in 1962. See Sec. 9.8 below.

But as each strand separates from the other, each acquires new complementary bases similar to those it formerly had, with the result that eventually each strand becomes a new double helix with a structure similar to the original. From a biological point of view, the important thing to note is that the particular sequence of bases in the DNA molecule carries a code in which genetic information is stored. Thus, when the molecule is replicated, the same bases are strung along the spiral in the same order, and thus carry the identical message contained in the genetic code.[20]

Precisely how the information contained in the genetic code comes to be used within the organism does not lend itself to simple explanation. A key factor in the process is a special type of RNA molecule called messenger RNA or mRNA, which is so similar in structure to DNA that it can be formed by the template replication of DNA. The RNA so produced is then able to carry stretches of the genetic code (otherwise known as "genes") to places in the cell where proteins are manufactured.[21] Specific proteins and enzymes are there synthesized, in reactions that involve the compound ATP and another type of RNA molecule called transfer RNA or tRNA. The end result is that the genetic information contained in the original DNA molecule is reproduced in such a way that new molecules can be formed to duplicate those with which the process started. Not only is molecular *replication* involved, but also true molecular *reproduction*, and that is what ultimately underlies the reproduction of organisms we observe at the level of sense experience.

Worthy of note in the process just sketched is that each strand of DNA in the original is conserved during its replication. This has important consequences when one considers how genetic factors are passed on not only within an organism but from one organism to another, as in organismic reproduction. In the latter case there would seem to be direct transmission of an actual physical entity from one generation to the next. With human organisms, where the offspring is formed from a single fertilized egg, this could mean that the original strands of DNA forming the chromosomes from each of the parents are never destroyed, but rather are unwound and wound again untold numbers of times as the new organism develops. Somewhere in each individual, therefore, might be

20. The Nobel Prize for physiology in 1968 was awarded to Robert Holley, Hans Gobind Khorana, and Marshall Nirenberg for deciphering the genetic code that determines cell function.

21. A single gene was first isolated by Jonathan Beckwith and coworkers in 1969; this was a bacterial gene involved in the metabolism of sugar. It is estimated that there are over two million genes for a given human being.

found the original strands of DNA it inherited from its parents—not copies, but apparently the same atoms and molecules that once were parts of the parent organisms. If this were true, it could have implications for the human gene pool in general, for it would mean that the genetic information of all our human forebears—all the way back to our "first parents," to use the biblical expression—is still extant somewhere in the genes of persons living in the present day.

Such speculation poses an interesting problem from the viewpoint of natural generation as this has been described in the previous chapter (Sec. 2.6). Without questioning the copying process whereby genetic information may be transmitted from one generation to the next, one might question whether it makes sense to speak of the atoms and molecules that enter into the structure of DNA as being "the same" after a substantial change across generations has been effected. What is involved here is again the problem of individuation, and particularly how one can speak of parts of substances—say the chlorine atom within the salt crystal and the chlorine atom within the gas produced when salt is dissolved and decomposed by electrolysis—as maintaining a distinctive identity independently of the substances of which they are parts. In the first case the atom is an integral part of salt, in the second it is an integral part of chlorine, substances that have radically different properties. If the substances have different properties, why should their parts be thought of as unaltered? It would seem more correct to regard the substances' components as parts that obtain their substantial identity from the substances they compose. Thus, when a new substantial form takes over in the generative process, the parts themselves formally change even though they remain materially similar, and so can no longer be regarded as substantially "the same."

3.4 Modeling a Plant Nature

What has been said thus far about organic natures is very general, stressing mainly their relationships to inanimate nature and explaining the basic life functions that are common to both plant and animal kingdoms. Enough has been explained, however, for us to proceed now to a fuller discussion of plant natures in a way that will serve to differentiate them from both inorganic natures and animal natures. Our goal here is synthetic rather than analytical, to put together the powers and functions that are typical of vegetative life, even though they are found also within the animal kingdom. In the foregoing sections we have already touched on the basic power of control, homeostasis, and on the role of metabolic processes in supplying food to the plant organism from the nutrients available to it. We also have discussed the powers of development and reproduction, which serve to explain how plants grow and propagate. Now we must elaborate briefly on the diversity of speciation within the plant kingdom, to give some idea of the various structures in which all of these powers operate. With this as a basis we can then examine how such variety is reducible to a functioning unity within the individuals of a particular plant species, on the pattern of what we have already explained in the preceding chapter about inorganic natures and their functioning.

It goes without saying that there is great diversity in the plant kingdom, comprising as it does a vast number of known species. These are usually divided by biologists into three phyla: the algae and fungi, the mosses and their kin, and the vascular plants (including ferns and seed plants).[22] Within the first phylum the algae are differentiated from the fungi in that the former contain the green pigment chlorophyll whereas the latter do not; in some algae, however, the green color is masked by additional pigments, thus giving rise to a variety of species—some green, others blue-green, yet others brown, and some even red.[23] Lacking chlorophyll, the fungi are never leaf-green, though they may be variously colored from other pigments; they do not manufacture their own food and thus must secure it either as parasites from other organisms or as saprophytes from dead or decaying organic matter. Lichens also pertain to this phylum; they are composites of algae and fungi that manage to live in symbiotic relationship with each other.

The mosses and their allies, constituting the second phylum, are somewhat inconspicuous green plants. Unlike the algae, which are generally aquatic, the mosses are by and large land-dwellers. They also differ from plants in the first phylum in that they possess a body that is more complex, being fitted with specialized reproductive structures.

The third or vascular phylum includes a great number of plants all of which are equipped with systems of vessels that serve to conduct materials throughout their bodies. They are the most highly developed of all

22. We make no attempt to enumerate the number of species in the various phyla. For the many problems involved in an accurate enumeration of plant and animal species, see Robert M. May, "How Many Species Inhabit the Earth?" *Scientific American* 267.4 (1992), 42–48.

23. Chlorophyll was first isolated as a chemical substance by French investigators Pierre Pelletier and Joseph Bienaimé Caventou in 1817. Its structure was not determined until 1905, when the German researcher Richard Willstätter made the discovery.

plants and usually possess large bodies with well differentiated tissue systems. Apart from a few species (e.g., club mosses and horsetails), their main division is into ferns and seed plants. There are many thousands of species of ferns; most of these are found in tropical climates, though they also flourish in temperate regions. They differ from seed plants in their method of reproduction, which is by spores rather than by seeds. The seed plants, on the other hand, are divided into two types. Some bear seeds within cones and so are without flowers in the usual sense. Others bear seeds within flowers and so are referred to as flowering plants; these break down into dicotyledons and monocotyledons. As the names suggest, the embryo sporophyte in the seed of the first contains two cotyledons or seed leaves, whereas that of the second contains only one. Vegetation on the earth's surface in the present day is mainly dicotyledonous; the herbs, shrubs, and trees of common experience make up this group. But the monocotyledons are also important: they include the grass family (including wheat, corn, oats, and barley), of great economic value for man, and the palms, lilies, and orchids, appreciated for their aesthetic appeal.

Notwithstanding the enormous variety of plant life, it is possible to characterize a plant nature in a way analogous to that already used to characterize an inorganic nature. This is diagrammed by the powers model shown in Fig. 3.5, which will be seen to reproduce some of the elements found in Fig. 2.6. Abstracting for the moment from the circles on the diagram, we may note that the four lower boxes represent the potentials or forces studied in the physical sciences. These are designated by the same letters as used previously: EF for electromagnetic force, GF for gravitational force, WF for weak force, and SF for strong force. Above these, in the four upper boxes, are shown the four natural powers required for vegetative life. On the lower level are two control powers designated by the letters HC and MC respectively: HC stands for homeostatic control, regulating the organism's links with the environment, and MC for metabolic control, regulating its internal processes of food and energy conversion. On the level above these are the two additional powers already discussed: the developmental power, designated DP, which effects cell differentiation and growth within the organism, and the reproductive power, designated RP, which brings about the production of new individuals within the species.

As in the previous diagram of the powers of the inorganic, Fig. 3.5 is a generic model applicable throughout the entire plant kingdom. When instantiated with any one type of organism, it is these powers and the natural form underlying them that actually develop the tissues and organ

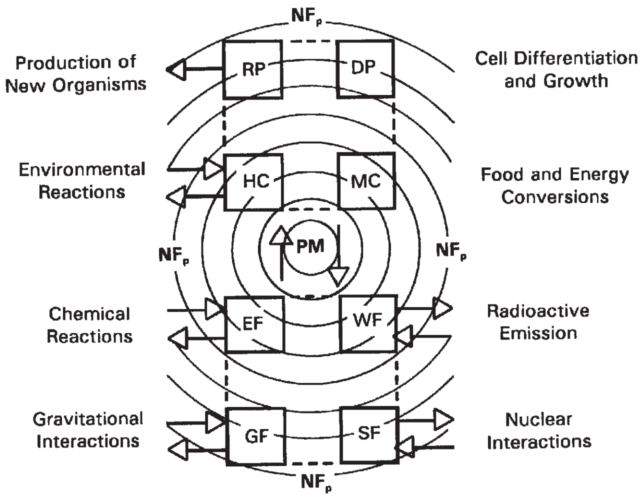

Fig. 3.5 A Powers Model of a Plant Nature

systems necessary for the life activities of the particular species. The basic material out of which these are formed is protomatter, represented, as heretofore, by the letters PM. The natural form that underlies the powers, that is, the specifying form that is the correlate of protomatter and determines the organism to be the type it is, is further shown as a series of concentric circles surrounding the protomatter. This is now labeled NF_p, with the subscript "p" meaning plant, replacing NF_i, where the "i" stood for inorganic. As heretofore the NF may be taken to stand for specifying form, because it fixes the plant's species; alternately it may be taken for substancing form, because it makes the plant an individual substance within that species; or again, for stabilizing form, because it acts to preserve the plant in existence throughout its lifetime.

The eight powers found in a plant nature are shown as boxes within the field represented by the concentric circles of the plant's form, NF_p. This mode of representation is intended to convey the idea that these powers are actually the powers of the form, the agencies through which it stabilizes the component parts of the plant and directs them to perform the functions characteristic of the species to which the plant belongs.

The model itself, as already stated, is a generic model, but its function is to represent the nature of a plant organism of a particular species or type, such as that of a live oak, or geranium, or moss, or alga. The adjective "live" is important, for only when it is added do we have a true oak or geranium, etc. When the tree or plant dies, the nature is no longer there, the powers cease to activate the organ systems, and the substance decomposes and reverts quickly to the level of the inorganic. But precisely as representative of a live organism within a particular species in this way, the organic powers become those of a determinate nature such as oak or geranium. In the case of an oak, they direct its homeostatic and nutritive activities, its growth and development from acorn to tree, and the processes whereby it eventually produces new acorns and other oaks. The mode of acting of an oak nature is different from that of other plant natures, such as those of maple, moss, or alga. Obviously oak is closer to maple than to moss or alga, in view of the latter's belonging to different phyla within the plant kingdom. And yet there is enough similarity to say that all four are plant natures and so exercise the same basic life functions.

To elicit some appreciation for the role of nature as a substancing form in a plant organism an additional observation may be made about its powers model. The lower portion of Fig. 3.5, as already remarked, duplicates the four powers of an inorganic nature, and yet these powers do not function in a plant in the same way as they do in an element or a compound. The two arrows on either side of the letters PM provide a clue to this in that they signal a coupling between the four basic forces and the vegetative powers shown directly above them. The latter powers are shown on top to signal that they provide a control over the chemical components in the plant's structure. Such control is effected by the two vegetative powers at the first level, HC and MC, homeostatic and metabolic control respectively, working mainly through the electrical and gravitational forces studied by biochemists, shown as EF and GF. In this fashion the basic energy requirements for life processes within the plant come to be provided. The way in which this nutritive energy is used is then determined by the developmental power (DP) on the right of the second level, which controls the distinctive patterns in which the plant grows (and stops growing), and finally by the reproductive power (RP) on the left, which channels energies of the adult form for the generation of new organisms.

Finally, it should be noted that some of the powers are shown with arrows directed inward or outward, that is, toward or away from the power. The outward-directed arrows indicate that the power is active and thus that it can make the organism an efficient agent; correspondingly, the inward-directed arrows show that the power is also passive or reactive, thus making it a reagent in physico-chemical processes. The simplest case of the plant being an efficient agent is when it produces a new organism, as shown by the outward-directed arrow on the reproductive power (RP). But when an oak tree topples over and crashes to the ground, crushing objects under it, these show it to be both reagent and agent through the gravitational force (GF) exerted on it, which causes it to act on other things. Similarly the many chemical processes that go on within the plant are effected mainly by electrical forces (EF) within its organic parts and the fluids they contain.

3.5 Sentience and Mobility

The animal kingdom is usually differentiated from that of plants by its possessing sentience and mobility, and for these characteristics additional powers and organ systems are required. Although one may speak of a plant's behavior, the term "behavior" is usually reserved for distinctively animal activities. Touching an oak tree may reveal little about life functions that are going on within it, but touching a frog gives a quick indication of whether the frog is alive or dead. The frog is able to sense that someone or something is touching it, and it is further able to move quickly in response to the stimulation. Yet not all animals have the ability to sense and to move with the agility of frogs. On this account it is desirable to survey briefly the various kinds of animals, as done above with plants, to provide a background against which the behaviors attributed to them may more readily be understood.

The major division within the animal kingdom is that between vertebrates and invertebrates, the former being backboned and the latter not. Usually when one speaks of an animal in the present day one has reference to vertebrates—the fishes, amphibians, reptiles, birds, and mammals of ordinary experience. But there are many species that have not reached the stage of development found in the vertebrates, and these actually make up the greater portion of the animal population.

The number of animal species is many times greater than that of plant species. The invertebrates are commonly regarded as primitive forms of animal life, having started with unicellular organisms such as the amoeba and then having developed into various multicelled types. The great number of invertebrates is accounted for by the almost innumerable species found among the arthropods, a phylum made up of insects, crustaceans, and other animals with articulated bodies and limbs. The more important remaining phyla are then the protozoa (also very numerous), the sponges, the polyps and related types, worms, and mollusks. The last named, possessing soft unsegmented bodies usually enclosed by a shell, includes snails as well as clams, oysters, scallops, and other shellfish.

All invertebrates have some form of mobility, at least during their developmental phase, and all enjoy some type of sense life. Protozoa, for example, are commonly divided on the basis of their organs of locomotion. They include the flagellates, which are moved by a long filament-like appendage that protrudes from the cell; the rhizopods, such as the amoeba, which is moved by pseudopods or foot-like projections it sequentially forms and retracts; and the ciliates, such as the paramecium, which is moved by cilia or hair-like processes that cover its exterior. Some portions of the protoplasm of these organisms seem to be differentiated for receiving and conducting stimuli, whereas others are adapted to respond to stimuli by contracting parts of the cell, and so, in the paramecium for example, moving the cilia. In multicellular animals or metazoa, the developmental process early differentiates an outer tissue or ectoderm from an inner tissue or endoderm, and so initiates a separation between the ectoderm's functions of protection and reaction to the environment from the endoderm's functions of digestion and nutrition. The ectoderm then becomes the seat of specializations corresponding to the nervous systems and sense organs found in the higher animals. Such differentiation is difficult to discern in sponges, but it becomes clearly apparent in polyps and jellyfish, which form the basic phylum from which invertebrates seem to have developed. In the hydra, for example, ectoderm and endoderm are definitely established, with a mouth opening into a digestive cavity and with specialized body parts already coordinated by a simple nervous system.

Among the worms, the flatworm shows an advance over the polyp in that it exhibits bilateral symmetry and has a simple eye and a brain; its mouth, however, is not in the head but in the middle of the body, where it serves to take in food and eliminate waste. Its intestine, male and female reproductive organs, and weblike nervous system are not localized but rather extend throughout its body. The roundworm is further developed, for mouth and anus are at opposite ends of the body and there is definite articulation of its organ systems, with the male and female reproductive organs usually being found in separate individuals. The sandworm is of a higher order still, for it belongs to the phylum of segmented worms, possessing a more complex body whose segmentation allows for more localization of specific functions. Its head, for example, has a mouth with jaws, complex eyes, and sense organs, and its segments are equipped with paddlelike appendages that serve as both respiratory and locomotor organs.

Mollusks are distinctive in being surrounded by an external skeleton or shell and a fleshy, muscular organ that protrudes as a foot and is used for locomotion. Additionally there is a cavity between the main body and an enclosing envelope that secretes and lines the shell. Although most mollusks are sea-dwelling animals, a fair portion of them, such as snails and slugs, are terrestrial. Among the aquatic species, oysters attach themselves to undersea objects and thus have no use for the foot; their motion consists in actuating cilia that set up water currents and so bring nourishment into their mouths. Likewise of interest is another bivalve, the scallop, which is able to propel itself by rapidly opening and closing the valves of its shell to eject a stream of water. Also pertaining to this phylum are organisms such as squids and octopuses, which combine head and foot in a specialized organ and so are known as cephalopods. Though usually shell-less, they too propel themselves by jet; some types exhibit vestiges of the shell, however, as seen in the "bone" of the cuttlefish.

The arthropods constitute the most numerous and most advanced phylum among the invertebrates; some are chiefly aquatic and breathe by means of gills, as does the crayfish, whereas the rest are typically terrestrial and breathe air directly with tracheae, as does the locust. Their bodies are segmented and covered by a hard and unyielding exoskeleton with flexible joints, the sections of which are moved by attached muscles. They also develop paired jointed appendages as outgrowths from the body of each segment. These become organs for the performance of widely different functions: those of the head as sensory organs, of the thorax for grasping and walking, of the abdomen for swimming, and so on. The nervous system is correspondingly more highly developed: the brain is larger and sends nerves to the eyes, antennae, mandibles, stomach, etc.; and sense organs are more specialized—for example, the compound eye, sensitive tactile hairs, and in some types even a chemical sense for taste and smell.

This brings us finally to the vertebrates, whose major divisions are the fishes, the amphibians, the reptiles, the birds, and the mammals. As is well known, a fish is an aquatic, backboned animal that breathes by gills and swims by fins. An amphibian such as a frog may be thought of as a fish in its early life; at the end of its tadpole stage it discards its gills and develops lungs, replaces its fins by five-toed limbs, and begins a terrestrial existence. Reptiles such as the lizard may be seen as completing their tadpole stage in the egg and then emerging with lungs, scales, and limbs. Birds are warm-blooded animals that make their home in the air, replacing forelimbs with wings and scales with an insulating blanket of feathers, and developing ingenious ways of caring for their eggs and young. And mammals, finally, are warm-blooded, lung-breathing, usually hairy vertebrates that are nourished after birth by milk secreted from the mother's mammary glands. Despite the differences implied in these descriptions, the vertebrates as a whole are remarkably homogeneous both structurally and functionally: they all manifest bilateral symmetry, have a brain encased in a skull, an internal or endoskeleton, a spinal cord, red blood cells, paired appendages such as fins or limbs, and a tail.

3.6 Modeling an Animal Nature

The foregoing are the main features a zoologist might note in surveying the animal kingdom before analyzing the characteristics of the various phyla and then in greater detail the properties of individual classes and species. Our purposes here are quite different from the zoologist's, for rather than move in the direction of greater specificity, our task is that of moving in the opposite direction, toward greater generalization. And just as in the previous chapter we attempted to delineate the powers that lie behind the manifold activities and reactivities of the inorganic realm, and earlier in this chapter the powers that serve to explain the varieties of functioning of plants, so now we turn to the powers that complement these and so explain the greater diversity of activities found in the animal kingdom.

As should be apparent from the foregoing survey, sensation and motor activity are the principal factors that serve to differentiate animals from plants. The powers that lie behind these can now be investigated through the use of a simple model that has long been used to study animal activity, namely, the stimulus-response model of the behaviorists. In its primitive form this model appears as the simple "black box" shown in Fig. 3.6: the basic idea is that, when acted on by a controllable stimulus (S), the box will produce a measurable or observable response (R). In their desire to be "objective" and "scientific," as they then understood those terms, early behaviorists wished to dispense entirely with introspection and the mental processes associated with that technique. They thus professed to

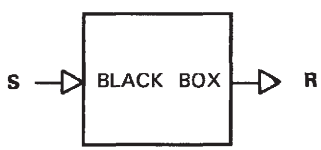

Fig. 3.6 The Stimulus-Response Model

be agnostic with regard to what went on in the box, relying exclusively on public methods of observation and so adopting the "black box" mentality. This bias has been vigorously rejected by the founders of cognitive science, particularly those interested in using computers to model the functioning of the mind and the brain. The success of programs the latter group developed for computer simulation has eventually sounded the death-knell of behaviorism and so initiated a revolution in the science of psychology.[24]

One of the earliest attempts to model animal activity with computers was made at the Burden Neurological Institute in London. The device was essentially an automaton or robot referred to as *machina speculatrix*; it received this name because it appeared to duplicate the exploratory or "speculating" behavior that characterizes animal life.[25] In its early form it consisted of two receptor elements, one a photocell sensitive to light, the other a relay activated by touch, and two effectors or motor devices, one for crawling, the other for steering. When set on a level board and suitably powered, the automaton, named "Elmer" (along with its mate, "Elsie"), could feel its way in the dark, steer around obstacles, approach a light source, solve the dilemma presented by two equal but separated light sources, and so on. A schematic diagram of these components is shown in Fig. 3.7. Here the single box of Fig. 3.6 has been replaced by two boxes, one labeled receptor and the other activator. Like the black box this is a stimulus-response model, but it differentiates the basic capabilities of the organism being modeled and permits a study of a wide range of interactions between them. The receptor is the photocell and the tactile relay, and the activator is the motor mechanism that gives the robot its cycloidal gait. The connecting circuits to the right of the diagram represent a computer that

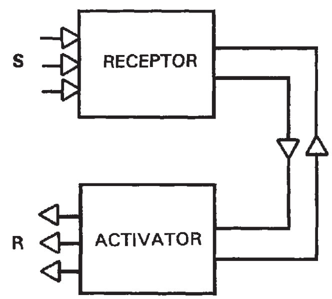

Fig. 3.7 *Machina speculatrix*

24. On this development see Howard Gardner, *The Mind's New Science: A History of the Cognitive Revolution*, New York: Basic Books, 1985, with a new epilogue 1987, 10–27.

25. Its inventor was W. Grey Walter, whose principal contributions have been in the use of the electroencephalograph to investigate the brain, particularly the relationships between brain waves and the gross manifestations of emotion, personality, and thought processes. The device is explained in the collection of essays *Automatic Control* cited in n. 12 above, pp. 126–127.

can be programmed to generate a variety of responses corresponding and reacting to the types of stimuli the robot encounters. For example, it can be enabled periodically to approach a special light source to recharge its batteries and so "obtain food." In this and other ways it can be seen to duplicate aspects of intelligent behavior such as the "purposefulness, independence, and spontaneity" claimed for it by its inventor.[26]

Subsequent developments in the field of artificial intelligence (or AI) have consisted largely in the development of more complex systems for the movement of robots, memory circuits that record sequences of events and so build up their "life experiences," and motivator devices that, when properly activated, initiate special types of activity. Recent examples of these will be found in the insectoids (or smart bugs) such as "Genghis" and "Attila" being developed at M.I.T. and elsewhere, about which more will be said in the following chapter. Like insects, these are multipedes (six legs, in the case of "Genghis"); they can lift and lower each leg and swing it back and forth, and so use their legs to rise from a sitting to a standing position and then to walk with different gaits. They are equipped with whiskers and infrared sensors, and in some cases with audio equipment, enabling them to detect obstacles and climb over them, and so on. Referring to these as "behavioral vehicles," researchers design them to perform multiple tasks in exploring a terrain, speculate how long they can survive in a hostile environment, and even ascribe to them emotions such as fear and longing.[27]

The development of these features suggests the more developed model illustrated in Fig. 3.8, where additional function boxes have been added to the simple receptor and activator shown in Fig. 3.7 to form both a receptor line (A) and an activator line (B). Here the receptor has been replaced by a sensor box and a memory box and the activator by a motor box and a motivator box, thus introducing a double capability into each line. Each of the four capabilities that results requires, of course, one or more microprocessors, along with software appropriate for carrying out the functions associated with it, and it must be energized with sufficient power to carry them out. Since the power requirement is critical for the operation of the robot, we shall henceforth refer to capabilities such as these as its powers, just as we have for our previous models. Actually they channel the energy provided to the robot in distinctive

26. Ibid., 127–131.

27. The design of one such artificial insect will be described in the following chapter, Sec. 4.4.

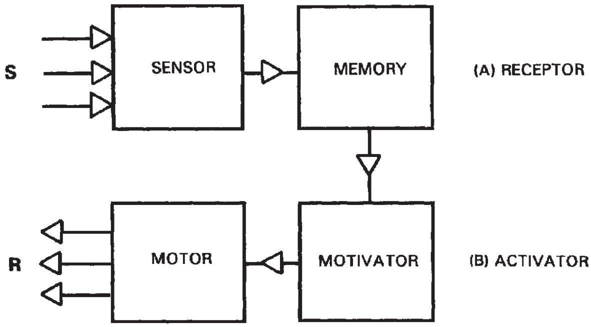

Fig. 3.8 A Schematic Robot Model

ways and so enable it to perform the many functions designed into it. Such powers, when activated by appropriate stimuli, become the source of the distinctive responses elicited from the robot. And these responses are not elicited in strictly deterministic fashion, but rather allow for the varying degrees of spontaneity and indeterminism resulting from the ensemble of computational devices that control the robot's "life activities."

With the reintroduction of the power concept, we are now in a position to discuss the modeling of animal organisms along the lines earlier pursued for plants. Here the computer model just developed in Fig. 3.8 can provide the basis for a "life-powers" model that captures the essential elements differentiating animal life from plant life. Of the four powers shown in Fig. 3.8, the one that most closely approaches the real-life equivalent in an animal is that represented by the motor box, for it is able to mimic fairly well various features of locomotion found in animals. The powers of the other three boxes, however, also have their equivalents in animal life, though they manifest more of artifice than they do of nature in the ways in which they perform their respective functions. The sensor power is obviously similar to the animal's five powers of sensation, those associated with the external organs of sense found in the higher animals, namely, sight, hearing, taste, touch, and smell. The memory power is suggestive of a different type of sensation, what Aristotle would refer to as "inner" sensation, that is, one directly associated not with an external organ but rather with the brain and nervous system. Memory, for him, provided sense knowledge of this type; so, too, did imagination and instinct. Beyond these he also required a fourth inner sense, the common or central sense, which he saw as necessary to integrate and coordinate the data being received from the external senses.

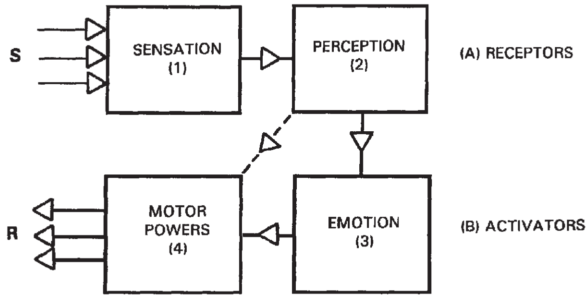

Fig. 3.9 Animal Powers

All four of these inner senses we now group under the rubric of perception, since they enable the animal not only to sense but also to perceive its environment and react properly to it. The reaction itself is then taken care of by the equivalent of the fourth power, that represented by the motivator box, which takes the place of emotions as these govern and control animal life.

This new ensemble of animal powers is diagrammed above in Fig. 3.9. This is essentially the same as Fig. 3.8, except for the appropriate animal powers being substituted for the artificial type incorporated into the robot. It likewise can be seen as a stimulus-response model that is able to explain animal behavior in a variety of circumstances. Objects in the outside world act on the animal organism through stimuli (S) that are translated into the various sensations received by the external senses (1). These are then processed through the internal senses (2) to form and retain representations of the objects sensed, commonly referred to as percepts. (Precisely what a percept is and how it functions in the knowledge process will be discussed in detail in Sec. 4.6 below.) The percept(s) so apprehended may immediately provide the basis for an autonomic or reflex reaction that triggers the motor powers (4)—shown by the dashed line—and so produces a response (R) that safeguards the good of the organism. Alternatively, the percept(s) may be mediated by an instinctive awareness of whether the object(s) perceived is (are) good or bad for the organism and so stimulate(s) an emotional reaction of pursuit or avoidance (3). This in turn activates the motor powers (4)—along the path shown by the solid lines—to produce a response (R), either one of approaching toward or one of retreating from the object(s) apprehended.

The four general powers of sentience and mobility, shown in Fig. 3.9 along the receptor line and the activator line respectively, must now be joined to the eight powers already described for plant life to supply the full complement of powers required for an animal organism. When this is done, we obtain the powers model of an animal nature shown in Fig. 3.10. This model is similar in all respects to those in Figs. 2.6 and 3.5. The place wherein it differs is in the four powers shown at the top, based on the robot model just discussed. The sensor of the robot has been replaced by the external senses, ES—sight, hearing, taste, touch, and smell; memory has been expanded to include all of the internal senses, IS, associated with the brain and central nervous system—perception, imagination, memory, and instinct; the activator has become behavioral response, BR—various emotional reactions as sources of impulsive or aggressive behavior; and the motor has been replaced by the range of motor powers, MP, required for the animal's organs of movement.

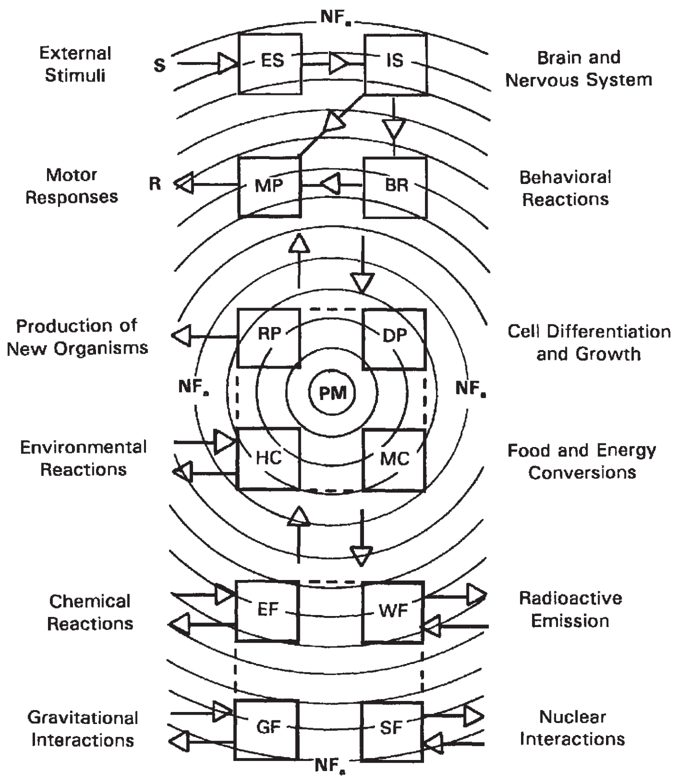

Fig. 3.10 A Powers Model of an Animal Nature

These, added to the previous eight, make up twelve natural powers that serve to explain the functioning of an animal organism.

As can be seen from Fig. 3.10, all of these powers are interrelated in a type of hierarchical structure wherein the four powers of the inorganic subserve the four plant powers, and wherein all eight in turn subserve the powers that characterize the animal kingdom. The ensemble of these powers operating within the animal is what constitutes its nature or specifying form. This, as previously, is modeled by the radiating circles or field labeled NF_a, with the subscript "a" meaning animal, which energizes all the powers and enables them to function as a specific unit. This natural or substancing form is the ontological correlate of protomatter, PM, shown as before at the center of the figure.

Note again that the nature modeled in Fig. 3.10 is not a specific nature but is only generic in kind. To be fully understood it must be associated with an organism of a particular species, say, a squirrel. A live, adult squirrel is able to exercise all of these natural powers, and it does so in ways that contribute to the unity and well-being of the entire organism. Its life has an inorganic base in the sense that its bodily components obey all the laws of physics and chemistry. It also is able to provide its own vegetative functions—it assimilates its food and grows and develops, and eventually procreates its own kind. All of these functions undergird its sensitive and mobile capabilities. And although these latter capabilities can be modeled in some respects by robots, as already seen, the squirrel differs from robots in an important respect; it is self-developing and self-activating—another way of saying that it is alive. Robots work only when they are externally powered or energized; the squirrel is by nature energized. And yet the concept of being energized casts light on the function of the natural or substancing form in the realm of the living. Just as a robot is inert or dead when it lacks a source of energy, so the squirrel is dead when it is no longer animated, when it no longer has its nature, when the powers deriving from that nature become inoperative, and when its structure disintegrates and the organism itself decomposes into inert chemical substances.

3.7 Psychosomatic Components

Up to this point we have discussed natural and substancing forms and have broached the topic of animation, but we have yet not introduced the term soul. It is time now that we do so, for much of our development to this point has been based implicitly on Aristotle's *On the Soul*, a treatise known in Greek as *Peri psuchē* (thus the source of our term "psychology"[28]) and in Latin as *De anima* (the basis for our "animate" and cognate terms). Within the Aristotelian tradition this work enjoys a fundamental status for biology and psychology analogous to that of the *Physics* for the sciences of the inorganic. Yet there is a closer unity between these two works than one finds in their modern counterparts, for the *Physics* supplies the more basic principles on which even the *De anima* builds. Both the inorganic and the organic disciplines are viewed as parts of the larger Aristotelian science of nature, and thus the concept of nature (Gr. *phusis*, Lat. *natura*) provides the common link between them. Each has natural bodies as its subject and so is a natural science in an equal sense. In the present day we sometimes differentiate the physical sciences (physics, chemistry, astronomy, etc.) from the natural sciences (biology, botany, zoology, etc.) and so tend to obscure this common bond.[29]

Earlier we have explained how natural substances have natures that are rooted in the two principles of which they are composed, protomatter (PM) and natural form (NF). In Aristotelian science, protomatter functions as the basic and undifferentiated substrate that underlies the entire world of nature; on the modern scene, what we have identified as PM's quantifiable surrogate, mass-energy, performs essentially the same function in all the disciplines. Natural forms, on the other hand, are determinate and specifying; thus far we have classified them generically on the basis of the kingdoms to which natural substances belong, mineral, plant, and animal. This has yielded the three types for which we have provided generic models, NF_i for inorganic natures, NF_p for plant natures, and NF_a for animal natures. Although all three are natural or substancing forms, the latter two are different from the first: they are forms of the living, whereas the first is a form of the nonliving. To differentiate the two categories, the Greeks used a special term for animating forms, calling them souls. Thus, in their terminology, there are plant souls and animal souls (and, as we shall see later, human souls). Forms of the nonliving do not rate a special designation and so are referred to simply as natural or substantial forms. Yet all are natures in an actual or determinate sense, and all inform protomatter (nature in a potential or

28. The Greek letter upsilon is transliterated sometimes as a "u," sometimes as a "y," which is reflected in the two spellings, *psuchē* and *psychē*—the latter the root of our psychology.

29. Our term "natural" derives from the Lat. *natura*, which is a translation of the Gr. *phusis*, the source of our term "physical." From the viewpoint of their etymology, therefore, the natural sciences and the physical sciences are coextensive in meaning and application.

indeterminate sense; see Chap. 1 above, Fig. 1.3) to constitute a natural substance.

It should be noted that the term "soul," when used in this way, has none of the mysterious or occult quality that has come to be attached to it in modern thought. If a body or substance can be recognized as living, it is animated or besouled, that is, it has a soul as its life principle; if it cannot be so recognized, it is simply lifeless or inert. Thus, in effect, soul is used tautologically. If there are problems in understanding it, these are no more difficult than understanding what life is, or discerning the difference between a body that is alive and one that is lifeless.

To return to the example cited at the end of the previous section, a squirrel is a natural substance. Its nature is grasped by anyone who perceives, say, a gray squirrel, and says instinctively "That is a squirrel." A true squirrel, of course, is a live squirrel, so the presence of life or of a life principle is grasped in the very comprehension of what it is to be a squirrel. Then, if the squirrel ceases to move or to manifest the life activities associated with the species, we say that it has died. Its life principle has left it, and it ceases to be a squirrel, even though for a while it may continue to look like one. Lacking a specifying and stabilizing principle within it, its body decomposes. Its protomatter is informed successively by other natural forms, it becomes food for scavengers and so is subsumed into one or another living substance, or it breaks down chemically into many inorganic substances.

The case of the robot is obviously different. It is an artifact, not a single substance with a nature, but rather something put together from a variety of natural substances. The form that unifies its parts is not a natural form; no matter how complex its design, it is still an accidental or artificial form, the product of the ingenuity of its designer. All of the parts are inert or inanimate, and the robot is the same: it itself is lifeless. When its energy source fails or is removed, we may say that it has "died," but its "dying" is not the same as the squirrel's. All of the parts remain intact; each substance entering into its composition (with the exception, say, of expendable parts such as batteries) retains the nature it had previously; none disintegrates the way the organ of a squirrel disintegrates on the death of the organism.

Aristotle's definition of the soul attempts to capture this reality: it is "the first actuality [Gr. *entelecheia*] of a natural body having life potentially in it," that is, of a natural body equipped with organs that are capable of supporting life activities.[30] In the fourth century B.C. thinkers

30. *On the Soul*, II.1, 412a3-b9.

were not aware of any structure or heterogeneity within the inorganic substances found in sense experience; yet organic substances, as they could see, had parts that are diversified. A part of this type they called an organ (Gr. *organon*, meaning instrument), and the substance that possessed it an organism. They thus characterized plants and animals as organisms and so differentiated them from earth and water and gold and emeralds, which obviously are not.

The differentiation of bodily parts into organs suggests a further diversification of the soul into corresponding parts. Since the Greek for soul is *psuchē* and that for body is *sōma*, we may refer to such parts as psychosomatic parts, that is, parts of the soul that have counterparts in the body. Higher animals, for example, have eyes with which they see; a dead squirrel, on the other hand, may have eyes (for a while at least) but it is unable to see. The difference between it and the live squirrel comes from the latter's natural form or soul, which when present not only activates or energizes the body as a whole, but energizes all of its parts, though each in a different way. The activity (Gr. *energeia*) it produces in the eye is that of sight; because it can enable the organism to see, we say that the soul has the power (Gr. *dunamis*) of sight. Yet it is limited in this to some degree by the physical state of the organ. If the eye is defective, for example, the animal may be blind, even though it is alive and its remaining organs are able to function normally.

Psychosomatic parts are obviously not extended or quantitative parts, and so the term part when used here is open to misunderstanding. On this account it is better to refer to them as components, as entities that enter into the composition of the soul. Then, if they are called parts, they are to be thought of as power parts, or simply as powers. Just as one speaks of the body and its organs, one can then speak of the soul and its powers. The analogy or parallel is quite apt: the body is composed of quantitative or integral parts; the soul is similarly composed of qualitative or power parts. For each distinctive organ or organ system in the body there should then be a corresponding power in the soul that energizes that organ or organ system to perform its proper vital activity. Viewed in this way the soul itself is the primary principle whereby the organism lives; its powers are various secondary principles that enable it to perform the life functions proper to its species using the organs with which the body is endowed.[31]

31. This way of stating things corresponds to Aristotle's second definition of the soul elaborated in *On the Soul* II.2, namely, "the soul is primarily that by which we live or sense or think" (414a13–14).

The psychosomatic parallelism just sketched can now shed light on the generic models for plant and animal life presented earlier in this chapter. In the model for a plant nature, Fig. 3.5 above, the plant soul or natural form (NF_p) is shown as an energizing field radiating out from protomatter and enlivening the entire organism; at strategic places within the field, boxes have been superimposed to represent the soul's various powers. The diagram is only schematic: the localization of the boxes has no particular spatial significance. For example, the topmost box on the left designates the plant's reproductive power (RP), which empowers or energizes the plant's reproductive organs. These organs are indeed localized within each organism, but considering the wide range of plant types and their ways of reproducing it is not possible to indicate in a generic representation precisely where they are localized. If the organs are healthy and the organism mature, the plant will sooner or later produce one or more new organisms like itself. This production is indicated by the arrow emerging from the left side of the box. The topmost box on the left stands for the plant's developmental power (DP); as indicated in the figure this takes care of cell differentiation and growth within the organism. Such growth takes place throughout the plant's interior and not merely at its surface extremities, the way a crystal is said to "grow" in a solution. The locus of this power's activity is thus in the cells themselves and so is diffused throughout the entire plant. This perhaps casts light on the functioning of the "morphogenetic field" in the plant's development. Individual cells grow, but the plant also grows as a whole and as a natural unit of its species, and it is this regulation that is achieved by the soul's developmental power.

The two boxes shown under those for the reproductive and developmental powers are control powers, that on the left for homeostatic control (HC) and that on the right for metabolic control (MC). These function more like the developmental power than the reproductive; they too operate throughout the entire organism. Homeostasis is an internal, self-regulatory control that maintains balance and equilibrium within the organism. It also enables the plant to react within limits to its environment and so sustain life when possible, even under extreme conditions; this function is shown by the inward- and outward-directed arrows on the left of the box. Metabolism is, of course, more closely linked with the developmental power, for it regulates food and energy conversion that nourishes and sustains the organism on a continuing basis throughout its life; it likewise provides for growth and development at particular periods. It functions biochemically with the powers of the inorganic shown in the bottom half of the diagram, to be explained more fully below.

When we come to the diagram for an animal nature, Fig. 3.10, we notice that this is much more complex than that for a plant nature; the energizing field is larger and it contains more boxes. All animals, as previously indicated, require powers for sentience and mobility over and above vegetative powers; moreover, higher animals such as vertebrates have organ systems that are more numerous and better articulated than those of plants and require fuller representation.

As with the plant nature, the animal soul or natural form (NF_a) in the diagram radiates out from protomatter and enlivens the entire organism. The topmost box on the left is now labeled ES, for external sensation; this represents a complex power that enlivens the various external senses—the eye, the ear, the nose, the mouth, and the skin surfaces generally, together with the nerves that connect them with the central nervous system and the brain. Lower animals do not possess all of these, but they are found in vertebrates and a fortiori in humans. Each power of external sensation is obviously localized within its corresponding organ system. If the animal is healthy and its organs properly formed, it will see, hear, smell, etc., in normal fashion; otherwise it may be blind or deaf, yet still alive, though probably not for long if located in an environment with predators. The topmost box on the right, labeled IS, represents the powers that take care of internal sensation. These are localized in various ways within the central nervous sytem and the brain, and their functioning will be discussed in later chapters. Immediately under the box for external sensation is one labeled MP, for motor powers. The organs that these powers activate are many and diverse, as can be gathered from the brief survey of them in Sec. 3.5 above. Next to them, on the right, is the box for emotional response (ER), representing the powers that control the appetite or emotions and the various kinds of behavior found in the animal kingdom. The discussion of these powers will likewise be deferred to later chapters.

Beneath the powers for sentience and mobility, at the center of the diagram, are boxes for the four vegetative powers already treated when explaining the diagram for plant life. An animal is not a plant, and yet within the animal organism one can find all of a plant's functions being exercised, only now adapted to meeting the special needs of animal life. And finally, beneath them, will be seen the four powers of the inorganic realm. These again, like the vegetative powers, have now become animal powers, enabling the animal soul to use the chemicals incorporated into the organism at birth or ingested subsequently to sustain its various life activities.

Aristotle, as remarked above, had no suspicion of the possibility of structures in the nonliving world that would support the activities and re-activities of an inorganic natural form. Inanimate substances, for him, were homogeneous throughout, and thus they had no parts that could be differentiated and so serve as instruments of the whole for action or re-action. Again, the individuation of substances is more difficult to see in the realm of the nonliving, and so it is harder to discern numbers of sub-stances of the same kind. Add to this the fact that an inorganic form is not a soul, and so it is not proper to speak of psychosomatic powers in its case. Yet, after seeing the way such a form can be modeled using the findings of modern physics and chemistry, one is tempted to apply anal-ogous terminology to gain an understanding of inorganic natures. This, in effect, is the path we have followed in Chap. 2 above. It will be help-ful, therefore, to return briefly to Sec. 2.9 and particularly to Fig. 2.6 to explain more fully the model of inanimate substance there proposed.

Earlier in Chap. 2, in Sec. 2.4, we sketched the activities and reactiv-ities of the inorganic in terms of the four basic forces of high-energy physics; these are the agencies through which elements and compounds, and even subatomic entities, seem to act on each other. Some of the forces have potentials associated with them, so it is a simple matter to make the transition to powers and speak of them as powers. (The Latin term for force is *vis* or *virtus*, and both terms are commonly translated into English as power.) In Fig. 2.6 we labeled the boxes containing the four forces EF, GF, WF, and SF respectively, retaining the F for force rather than using the P for power, and we have retained this notation in Figs. 3.5 and 3.10 also. Whether F or P is used, however, the idea is still the same. We are attributing to the natural forms of the nonliving pow-ers through which they act, analogous to the *vis gravitatis* of the me-dieval era and the *vis inertiae* of Newton in early modern thought (see Secs. 9.6 and 10.6 below).

Gravity, as has been said, is the least understood of the four forces. Apparently it is associated with mass and is pervasive wherever mass is, that is, in practically all matter at rest. The other forces, as we have at-tempted to explain, seem to be associated with various parts of the atom: electromagnetic force mainly with the electronic configuration of the atom, particularly the outer shell; the weak force and the strong force both localized within the atom's nucleus, though associated with differ-ent components there. All of these forces or powers are the agents through which an inorganic nature, say, sodium or lead or radium, man-ifests its properties and reactivities when acted upon by other sub-stances, illustrated in various ways throughout the previous chapter. And when inorganic substances are subsumed into plants and animals and become parts of these organisms, either constituting their organs internally or serving as food or nutrient for them, these powers can also come under the control of the specific plant nature or animal nature. They will do so in various ways depending on how they are involved in the organism's metabolism. There is thus a continual interplay between these inorganic powers and the organism's metabolic (and homeostatic) control. Such an interplay is signified by the upward- and downward-directed arrows connecting these two controls with the four forces in Figs. 3.5 and 3.10 respectively.

To recapitulate, stable natural forms in the plant and animal kingdoms are known as souls within the Aristotelian tradition. Recognition of this fact is of help when explicating the concept of power as applied to natural processes, and it will be of further help when discussing problems relating to human nature in Chap. 5 below. But this terminology is not essential to the enterprise of this chapter, for plant and animal souls may be seen simply as natural forms, as explained in its early parts. The latter procedure offers the advantage that it establishes a much-needed link between the organic and the inorganic realms. Some of the wonders of the quantum world of the atom, for example, do not seem so extraordinary when seen in the light of the comparable wonders in living organisms.

With this the stage has been partially set for the study of human nature. Our treatment of animal natures to this point has been brief, for we have focused mainly on the movements of animals and have not gone into detail on what lies behind those movements, namely, their sentience. To complete the picture we must now address some of the problems associated with the acquisition of knowledge, during which we shall treat sense knowledge, the type of knowledge that animals have in common with humans. We do this in a transition chapter entitled "The Modeling of Mind," during which we also begin to explore problems that are peculiar to human knowing. With this as a background we will be in a better position to undertake, in the succeeding chapter, a more complete study of the human organism.

4 The Modeling of Mind

Our discussion of animal natures in the preceding chapter has concentrated to a large extent on the powers they have in common with plant natures. The distinguishing features of organisms within the animal kingdom, as has been noted, are their sentience and mobility, but apart from identifying the powers from which these activities originate, we have offered little by way of explanation of them. In this chapter we propose to remedy this deficiency by elaborating on these features, and particularly on sentience, for this is inextricably tied to animal movements of various types.

By sentience we mean simply sense knowledge in general. Thus understood, sense knowledge is a special type of knowing, namely, that attained through the senses. So as not to prejudice the investigation of other knowing processes available to humans (as opposed to lower animals), we take the position that the senses alone do not exhaust the possibilities for knowing. In particular we allow for another type of knowledge as proper to or characteristic of humans, namely, intellectual or rational knowledge. Thus we see knowledge as a generic concept that, at a minimum, includes sense knowledge and intellectual knowledge as its species. Since the general aspects of things are usually easier to characterize than the specific, we begin with a brief exposition of knowledge in general and proceed from this to our treatment of sense knowledge. This then serves as a propadeutic to our investigation of knowledge that is properly human, which occupies a major, though later, part of the chapter.

In following this procedure we are in effect explaining the powers of animal natures and human nature that are cognitive or concerned with knowing. The rubric under which we do so is that of the chapter's title, "The Modeling of Mind." As already noted, little is gained from using the term soul when referring to the natural forms of plants and animals, though it will be used to advantage in Chap. 5 when treating of the human soul. For present purposes we accede to modern usage and take mind as a surrogate for soul, thus replacing the couplets of *morphē-hulē* (form-matter) and *psuchē-sōma* (soul-body) with that of mind-body. Such usage brings with it all the baggage of the so-called "mind-body problem," but it also offers an entry into much of the recent literature on cognitive science. This new discipline, which has been characterized as "the mind's new science," makes extensive use of computers in its investigation of artificial intelligence. Thus it is able to supply a variety of models and analogies that aid in the understanding of natural cognition. We have already employed this technique in our discussion of robots in the preceding chapter, and propose to expand on it in what follows.

4.1 Cognitive Science and Cognition

The expression "cognitive science" seems to have first come into use in 1956.[1] Its proximate foundations were laid around 1948, when it began to take form as a reaction to behaviorism as a psychological theory, but its deeper roots can be traced to World War II and the years immediately preceding. Whereas the behaviorists had treated the knowing subject as a black box, a box in whose contents they professed no interest, the cognitivists felt that the box's contents should be explored, and they actively promoted the study of mind and mental processes. Part of the latter's motivation sprang from interest in neural physiology, especially the role of neurons in thought processes and their stimulation and simulation with electric currents; part of it came from the development of electronic devices for control purposes and for the transmission of information; part of it arose from advances in computing through the use first of vacuum tube circuits and then of transistors and silicon chips. Behind it all lay basic research into the foundations of mathematics, which was accompanied by a growing interest in mathematical logic throughout the early decades of the twentieth century.[2]

In the last decade of the century the key features of cognitive science may be characterized somewhat as follows. Its basic assumptions are

1. Howard Gardner cites this year as that of the birth of the discipline: see his *The Mind's New Science: The Birth of the Cognitive Revolution*, 28. Much of this summary of the key features of cognitive science is based on his treatment, 3–45.

2. Information is transmitted in bits, which require binary number systems. The 1's and 0's here are equivalent to the T's and F's of symbolic logic, and they can be repeated by open and closed electric circuits. Thus all three are interconnected—information, logic, and electronics.

two: first, that the use of mental representations is essential to understanding cognitive processes in animals and humans; and second, that computers offer the most effective tool for investigating such representations. Apart from these there are no pervasive principles that lie behind the discipline. Surely it is not a unified science in the sense that Newtonian mechanics or evolutionary biology may be said to be sciences. Rather it may be characterized as an interdisciplinary venture that draws its inspiration from a number of fields, among which one may enumerate computer science, mathematical logic, neuroscience, philosophy, psychology, anthropology, and linguistics. Such a broad sweep inevitably entails that those working in the field are accustomed to considerable ambiguity in their definition of terms and basic concepts.

This breadth and generality, together with its lack of univocity, may explain why cognitivists see their discipline to be in continuity with philosophy and do not shy away from the discussion of its classical problems. Despite this general orientation, however, and despite the fact that one finds in their literature an occasional reference to the Greeks, most of the philosophical discussion takes its origin from Descartes and then settles into Hume and the empiricist tradition, which dominates from there on. Aristotle is rarely discussed, and when he is, he is seen as an empiricist and a materialist; other interpretations of his thought are simply dismissed as lacking in interest. A fortiori no attention is paid to the rich development of the Aristotelian synthesis in the Greek, Arabic, Latin, and Renaissance traditions that furnish much of the background for this study.

Another peculiarity of cognitive science is its skirting of problems relating to the affective or emotional aspects of knowledge processes, or to the overall impact of history, culture, and context on them. Possibly this derives from the computer orientation dominant within the discipline, for aspects such as these have proved refractory to simulation with electronic devices. Practicality has thus thrust those working in the field towards developing an "antiseptic" cognitive science that ignores features of cognition that resist investigation with their favored tool of research. This is somewhat unfortunate, particularly since philosophers of science interested in psychology have recently been moving in the direction of intentional systems, wherein cognition tends to be identified with "belief," a term with distinct motivational overtones.[3] How beliefs

3. In the traditional understanding, belief differs from knowledge in that believing requires some type of motivation external to the knowing power, whereas knowing involves the actuation of that power alone (see Sec. 7.7 below). For an overview

and intentions can come under consideration by cognitivists is apparently a problem that still awaits solution.

A final consideration related to the foregoing is the programmatic field of study known as artificial intelligence or AI. Taken literally the name suggests a clearcut distinction between natural intelligence, the genuine kind found in knowing organisms, and artificial intelligence, the simulated kind that is unnatural and the work of artifice. As the field has developed, some of its practitioners have gotten away from this meaning and have taken a different approach. The difference in approaches is based on a different underlying philosophy, with the opposed viewpoints being identified as mentalist and materialist respectively. Those who subscribe to the original program are the mentalists: their conviction is that mental processes, and particularly those of humans, are too complex to be duplicated without remainder by machines, no matter how sophisticated they may become. The dissenters are the materialists, the more extreme among them calling themselves eliminative materialists. These are the "true believers" who see no essential difference between machine intelligence and human intelligence and so hold that machines actually think. The difference, sometimes referred to as that between the "weak program" and the "strong program," further suggests a difference in aims. The first is content to see computers as modeling certain aspects of thought or intelligence and as providing a useful tool for the cognitive psychologist. The second is more ambitious and proposes to show that, empirically at least, there is no way of distinguishing machine thought from human thought and thus the two may be seen as equivalent.

For purposes of this study the type of information provided by the "weak program" is all that is required and indeed proves to be more compatible with our overall objectives. The major problem is one of adapting that information to the Aristotelian terminology developed up to this point. Owing to the lack of consensus on the meanings of such terms as mind or mental, we first take mind to be the correlative of body, and so see the mind-body couplet as paralleling the historically prior couplets to which we have already made reference. form-matter (*morphē-hulē*) and soul-body (*psuchē-sōma*). This comparison makes

of the recent development among philosophers of science see Daniel Dennett, "Three Kinds of Intentional Psychology," in *The Philosophy of Science*, ed. Richard Boyd et al., Cambridge, Mass.: The M.I.T. Press, 1991, 631–649. This essay appeared earlier in *Reduction, Time and Reality*, ed. R. Healey, New York: Cambridge U.P., 1981, 37–61.

mind the equivalent of the natural form or the soul of a sentient or rational organism. Such an equivalence has obvious limitations, the main one being that the concept of the mental when employed in this way takes on too broad a connotation. Its reference must be contracted if it is to be applied exclusively to knowing powers, since even in the case of the sentient organism the natural form, as schematized in Fig. 3.10, has more powers than those relating to the acquisition of knowledge. Since our concern in this chapter is exclusively with cognitive powers, it is these powers alone that we shall henceforth take to be "mental" and the proper referent of the word "mind."

As to the term "cognitive" itself, this obviously refers to cognition (Lat. *cognitio*, from the Gr. *gignōskein*, to know), that is, to knowledge taken in its broadest sense. The term can have many referents: it may refer to the act whereby one knows someone or something, or to the act or activation of a cognitive power in the knower, or to the habit by which one can recall such an act, or, derivatively, to the matter that can be the object of such an act or habit. Knowledge that is contained in books or on computer diskettes belongs in the last named category, and as such it is dependent on the prior categories, that is, on habitual or actual knowledge, for its existence and coming to be.

Knowledge or knowing is difficult to define, but for purposes here a preliminary definition might be simply the presence of an object in a subject. The object is the thing known and the subject is the knower; thus the presence in the knower of something that is known constitutes knowing in its basic sense. When someone knows an apple, the apple, apart from the existence it has outside the knower, comes to have an existence within the knower also. All knowing, on this account, has both an objective and a subjective character: it is knowledge of something, an object, and this makes it objective; it is knowledge possessed by a knowing subject, and as such it is also subjective.

In another way of stating this, cognition, or the knowledge act, is not doing something but becoming something. It is a modification of the knower brought about by the objective possession of a thing other than itself. The knower's being is expanded by something not previously possessed, and this something is contributed by another that has lost nothing in the giving. This can be seen by contrasting the process of knowing an apple with that of eating an apple. When an apple is eaten it loses its being to the eater, whereas when it is merely seen it retains its own being and additionally shares it to some extent with the seer. In the latter case there has been no change analogous to that sketched above in Sec. 2.6, where matter loses its own form when it receives a new one.

The natural form of the apple, the thing known, remains the same, and the form of the knower does also, except that it has been modified in a cognitive way by the addition of a new type of form that makes the apple be present to it.

Unlike the process by which wax is imprinted by a seal and so receives the contours of the seal, this new form is not readily detectable and is usually recognized as present only by the one seeing. From this one can gather that the new form is present in the knower in a way unlike the material way natural or physical forms come to be present. To differentiate the two, the new presence is termed immaterial,[4] thus indicating that it is not received in the knower in a physical way, the way a natural form (NF) is united to protomatter (PM). Such a presence is also referred to as mental, for it is similar to the way objects come to exist in the mind. Yet another term is intentional, and so one speaks of the object known as having an intentional presence in the knower.

These clarifications permit us to modify the preliminary definition to read now: knowledge (or cognition) is the intentional (or immaterial or mental) presence of an object (the thing known) in a subject (the one knowing it). This presence is effected by a representation in the knower which may be referred to as a mental representation, using the cognitivist terminology mentioned above. Note that this definition of cognition is very general, and so there will be different types of representation according to the different types of knowledge one may possess. Characterizing these different types will be the main task undertaken in this chapter.

It should be apparent from the analyses offered in the preceding two chapters that not all natures or natural forms are equipped with powers that enable them to form intentional representations. Inorganic natures obviously are not so endowed, and even many organic natures, specifically those of the plant kingdom, give no indication of possessing them. Sentience, the lowest form of cognitive activity, seems first to be found in the animal kingdom, and on this account having an animal nature appears to be the minimum requisite for being a knower. Knowledge itself is then the result of a vital operation, a life activity that originates in a power of the animal's natural form and is perfective of the agent that pro-

4. The term "immaterial" takes on different meanings depending on its context. For a discussion of these variants see the author's "Immateriality and Its Surrogates in Modern Science," *Proceedings of the American Catholic Philosophical Association* 52 (1978), pp. 28–38; reprinted in *From a Realist Point of View*, 2d ed., pp. 297–307.

duces it. To be a knower an organism must be able to, or have the power to, transcend the distinction between itself and another entity in the natural world and so become that other in an intentional way. This it does by way of increase: remaining itself, it becomes also the other. The knower overcomes its material limitations, is no longer confined within its own spatio-temporal frame, and so enjoys a more perfect mode of existence than beings that are unable to initiate cognitive activities of this type. It is on bases such as this that animal natures are regarded as more perfect than plant natures, as already remarked in Sec. 1.5 above.

4.2 Sensation

The foregoing description of knowledge is quite general. It can be made more specific by discussing the two main types of knowledge found in the animal kingdom, sense knowledge, which is characteristic of subhuman animals, and intellectual knowledge, found only in humans. The difference between the two types of knowing is ultimately based on the different ways in which their respective mental representations are received. In the case of sense knowledge the concrete, individual forms of an object, that is, its visible, palpable, audible features, stimulate the organs of the knower and impress a variety of intentional forms on its corresponding knowing powers. In intellectual knowledge the mind draws on the sensible experience contained in these sensible forms and from them extracts intentional forms of a different kind. Rather than being concrete and individual, as are sensible forms, intellectual forms are abstract and universal representations of the mind's objects, commonly referred to as ideas. The first type of representation is discussed in this and the following section, the second in the later sections.

Sense knowledge, the simplest and basic type, is the knower's primary contact with the external world, effected through one or another of its organs. The organs for this type of cognition are usually referred to as senses, and they are further divided into two kinds, external (outer) senses and internal (inner) senses. Most of the organs of the outer senses, as their name indicates, are located on the periphery of the body. Organs of the inner senses, to the extent that they can be identified, are to be found in the central nervous system and the brain.

The term "sensation" is usually reserved for the product of one of the outer senses; this results when a sense of a living organism is properly activated and produces its intentional form. There are at least five of these external senses, namely, sight, hearing, smell, taste, and touch, and each puts the knowing subject in contact with one or another quality of the object sensed. Thus sight receives the sensation of color, hearing of sound, smell of odor, taste of flavor, and touch of softness or temperature. A sensation, in this understanding, would be the simple awareness of green, of a musical note, of sweetness, of heat, etc., without explicit reference to the particular object that would be bearer of these qualities. In all probability there are no such things as "pure" sensations that exist in isolation from other types of knowledge; yet it is possible to consider them in thought and analyze them as if they were to exist in independence of the other types. Individual sensations are of course separable, as is apparent from their lack in animals with organ defects; thus a blind person will not sense color nor a deaf person sound, though they will normally be aware of other sensible qualities.

The act of simple sensation may be seen as achieved in several stages. It begins with (1) the physical stage, wherein an outside stimulus (say, electromagnetic or sound waves) originating from an object impinges on a sense organ. This is followed by (2) the physiological stage, wherein a modification is produced by the stimulus in the sense organ. Since the organ is alive and animated, its physiological modification is accompanied by another, what we might call a psychic modification, whose production constitutes (3) the psychological stage. The result produced here is a likeness of the object, the intentional form already discussed. It is a substitute for the outside object within the sense power, by means of which the object, or the particular feature of the object accessible to the sense organ, is sensed or becomes known. Up to the formation of this intentional likeness the sense power can be regarded as passive or receptive. But knowledge is a vital operation, not a mechanical process. Hence the need for this last stage, the active psychological stage, wherein the sense power turns toward the object, grasps it, and knows it. Only when this occurs is there sense knowing, or sensation in the strict sense.

As already mentioned, five external senses are traditionally noted. Since the senses are passive powers, they are distinguished from each other in terms of what are called sensibles (Lat. *sensibilia*), that is, the objects that are capable of affecting them. Thus the differentiation of the external senses is a matter of properly understanding various stimulus-objects and receptor-subjects and of identifying the relationships that obtain between them. A stimulus is defined as an energy pattern that arouses a sensory receptor; the receptors that react to these specifically distinct stimuli are what we identify as the different senses.

Beginning with such a distinction of stimuli, one can note a difference among receptors by considering the proper organs, the nerves linking these organs to the brain, and the zones of the brain where the nerves terminate. In this way sight and hearing are very clearly distinguished. Smell and taste are similarly dissociated, despite the close chemical interdependence between them. Touch is more difficult to analyze, but it is generally seen as made up of the following functions: (1) tactile or cutaneous sensation that selectively responds to pressure, pain, warmth, and cold; (2) deep organic sensitivity, namely, kinesthesis or proprioception for muscular sensation, and deep touch for the viscera and internal organs; and (3) vestibular function, located in the semi-circular canals of the ear, for the positioning and movement of the body in equilibrium, a function that works in harmony with kinesthesis and deep touch. Various physico-chemical factors are involved in each of these types of sensation, but these need not be entered into at the general level here being considered.

The object of an external sense is called a sensible simply because it is able to modify a sense. Such an object appears as a complex ensemble that acts upon the senses in many ways. There are, first of all, qualities such as color that are capable of specifically stimulating a particular sense, in this case sight, to which they belong as their own immediate or "proper sensibles" (Lat. *sensibilia propria*). These qualities, moreover, exist as properties of quantified material realities; thus they are located in space and time and are subject to movement. They affect the senses in additional ways that are related to these quantitative aspects. For one, they may be measured in various ways, both extensively and intensively, as will be explained in Secs. 7.1 and 10.7 below. Moreover, because such aspects can act on several senses and are common to all of them, they are designated "common sensibles" (Lat. *sensibilia communia*). Finally, these quantitatively conditioned qualities manifest the natures of material realities, as well as their functional values for the knowing subject. Perception of these natures and of these values is made possible by the activity of the senses, but it requires more than simple sensation and involves other principles of knowing, such as the internal senses and, in the case of humans, also the intellect.

4.3 Perception

The outer senses, in this view, are not sufficient of and by themselves to produce a complete representation of the object sensed. The sensations they produce must be combined in some way to do this, and such activity is the work of the internal senses. Internal senses are called such because they have no end organs that face out on the world but must contact reality through the external senses. To identify them as principles of knowledge one must investigate functions of sense knowledge that are themselves irreducible to the external senses. These functions are then grouped around specific objects similar to those that serve to differentiate the external senses, the governing principle being that any function that cannot be referred to a single specifying object requires a distinct principle of operation.[5] Such a methodological principle is commonly used to identify four different internal senses, though not all are found in each species of animal. These are named the central sense, the imagination, the estimative sense, and the memory. The product of an internal sense is called a perception to distinguish it from the product of an external sense, which we have agreed to term a sensation. Sensations are the elements out of which a perception is formed, and the latter is like a composite image that originates, at the physiological stage, from the central nervous system and the brain. It then becomes, at the intentional stage, a mental representation or percept of the object sensed. (Note that the physical stage is not needed for the operation of the internal senses, since this is already supplied through the activity of the external senses.)

With respect to this percept each of the inner senses has a different function to perform. The central sense, known in the Aristotelian tradition as the common sense (Gr. *koinē aisthēsis*, Lat. *sensus communis*), integrates diverse sense impressions into the percept to form a unit of the knower's experience. The "common" in this expression is not to be confused with "common sense" as ordinarily used; it merely differentiates this sense from the outer senses, which are termed "proper" because each of them has its proper object not accessible to the others. But the central sense does more than combine sensations. It also makes the knowing subject aware of the different kinds of sensation and so to effect comparisons among them. It enables the knower to recognize, for example, that a particular sugar is both sweet and white. No proper sense can provide this type of knowledge, since it does not apprehend the objects of the other senses. On this accounting the central sense is requisite for the consciousness of sensation, and to the degree that sleep in-

5. Whether the internal senses constitute several different powers or are essentially functions of one or two powers is a debated issue. For Aristotle's teaching see Deborah K. Modrak, *Aristotle: The Power of Perception*, Chicago: University of Chicago Press, 1987. Two studies that address the problem directly are Rudolf Allers, "Functions, Factors, and Faculties," *The Thomist* 7 (1944), 323–364, and Magda Arnold, "The Internal Senses-Functions or Powers?" *The Thomist* 26 (1963), 15–34.

volves a loss of consciousness of this type it would seem to entail an inhibition of this sense.

The imagination (Gr. *phantasia*, Lat. *imaginatio*) registers the impressions unified by the central sense and is able to reproduce them subsequently. Its product is likewise called the percept (Gr. *phantasma*, Lat. *imago*), and it is at root the same as the product of the common sense. The difference arises from the fact that the central sense is unable to retain its own impressions; functioning in tandem with the external senses, it knows objects only when these actually affect the senses. The imagination, on the other hand, records the percept produced by the central sense and then has the ability to reproduce it at a later time. Its function is to "re-present" the percept, and in so doing it makes the percept into a mental "representation" in the proper sense of that term. More precisely, it is able to represent the sense object as it is past or absent or otherwise inaccessible to the external senses. (Apart from its role in sense knowledge, this mental representation then plays an indispensable role in intellectual knowledge, for, as will be explained in Sec. 4.5, it provides an image of a concrete reality from which the intellect can extricate the concept or the intelligible meaning latent within it.) Additionally, the imagination can be the source of error or illusion, for it is capable of representing images with new and fanciful elaborations and in this way distorting what has previously been perceived. But it can stimulate creativity at the human level, and it otherwise is involved in the dream, the illusory psychic phenomenon that occurs during sleep.

The estimative sense is closely associated with the imagination, and indeed it was not differentiated from the imagination by Aristotle. The first philosopher to articulate it as a special internal sense was Avicenna; he was followed in this by Averroes, Thomas Aquinas, and a host of Latin commentators, who henceforth refer to it as the estimative power (Lat. *vis aestimativa*).[6] Its function in sense knowledge, as the name indicates, is that of concrete evaluation or estimation. It employs data arriving from the external senses, the central sense, and the imagination to detect values whose perception escapes the other powers. Such values include the functional meaning of reality for the individual animal organism, that is, whether it represents something as beneficial or harmful, to be sought after or avoided, in given circumstances. The reason for positing it as a special sense is that animals have the ability to know what is good or bad for them, and this seems natural to them, for those of a

6. For an account of the historical development of this teaching, see G. P. Klubertanz, *The Discursive Power*.

particular species invariably judge in the same way. Knowledge of this type is not accounted for by the imagination, whose principal function is to retain and reproduce what was previously sensed. Since a certain intelligence and purposiveness is observable in animal activity, the instinctive and quasi-judgmental knowledge they suggest seem best attributed to a special sense.

Our consideration to this point has been cognition and cognitive powers, but in connection with the estimative power it should be noted that organisms possessing knowledge also have powers that incline them to seek or avoid the objects with which their knowing powers put them in contact. The generic name for such powers is appetite (Gr. *orexis*, Lat. *appetitus*), which means a seeking for something. In the strict sense appetite designates the capacity of a cognitive being to seek its good and avoid harm, but used more broadly it includes the actual seeking and avoidance as well, otherwise known as appetition. Various terms such as emotion, passion, urge, and drive give concrete expression to different forms of appetition. In the ensemble of animal powers diagrammed in the previous chapter (Fig. 3.9) all of the appetitive powers are grouped in the box labeled emotion, which is shown being directly influenced by the inner senses, there grouped in the box marked perception. But among the inner senses the only sense that produces a percept that is properly evaluative is the estimative sense, and thus the estimative is the power that immediately governs appetite and so initiates action. The good and the bad as recognized by an animal are concrete and individualized, and they are followed naturally by the emotions observed in animal behavior, namely, acts of desire, of fear, of anger, etc. This working together of the estimative power and sense appetite goes far to account for the quasi-intelligent behavior discernible in animal activity, otherwise explained by instinct.

The last of the internal senses is the memorative power or memory (Gr. *mnēmē*, Lat. *memoria*). Aristotle regarded remembering as a function of the central sense requiring the formation of a memory image or *eikōn*, but within the Aristotelian tradition this particular functioning, like that of the estimative in relation to the imagination, has come to be assigned to a separate power or sense. In the developed teaching, the memory sense plays a role with respect to the estimative power analogous to the role of the imagination with respect to the central sense. It preserves the percept with its functional values as apprehended by the estimative, say, with estimates of good and bad, so that the knower can re-experience what has happened before and recognize this experience as past. Thus the memory stores experiences and recalls them, not merely representing them as does the imagination, but rather situating them in a bygone present along an axis extending backwards in time. Memory makes animals that have this sense somehow aware of the past and so assures the continuity of their experiences as knowing subjects.

From the foregoing it may be seen that animal perception is a complex process that, in higher animals at least, involves all four of the inner senses. It provides awareness not only of the objects of sense experience, but also of space, time, and motion, and in general of the perceptual field in which the perceiver situates these objects. But precisely how such awareness is brought about constitutes a special field of research whose findings are beyond the scope of this survey.

Perception provides a unified knowledge of sensed objects that is more integrated than sensation and, as will be seen in subsequent sections, is more concrete and individual than intellection, the process whereby the concept or the idea is acquired. As has been noted, the distinction already made between sensation as an elementary experience and perception as the knowledge of particular objects is not meant to imply that the knower can experience sensation as distinct from perception. (A somewhat similar situation holds with regard to the relationship between perception and intellection, to be explained in Sec. 4.5. Apart from its role in the knowing processes of subhuman animals, the percept plays a key role in human knowing, and yet it is difficult for humans to experience the percept as distinct from the concept.)

For purposes of later reference it is important to delineate precisely what the percept does and does not contain. Its essential characteristic is that it represents a singular, concrete object as apprehended in past or present sense experience. Examples of percepts in a human would be the referents for expressions such as "this apple, large, red, and sweet" and "this rubber ball, bouncing up and down," or, more properly, the sensible representations that permit these expressions to be made. Such percepts contain more than individual sensations, since they themselves are composites of various sensations. At the same time they are not the same as concepts. Concepts, as will be explained presently, are abstract and universal, whereas percepts are concrete and individual. But percepts can be stored in the memory sense, and cumulatively they constitute the knower's total experience of the external world, the raw data or basic fund of information that guides all the activities of subhuman knowers and on which, in the case of humans, the intellect must draw for its various thought processes.

4.4 The Simulation of Sense Knowledge

Even from this overview of sensation and perception one can see that both forms of sense knowledge involve complex mental processes that are difficult to analyze and comprehend. An impression of precisely how complex such processes are may be gained from attempts to simulate animal activity with the aid of computers. In the previous chapter we mentioned a simple device that was developed at the Burden Neurological Institute in the 1950s to explore animal behavior, the *machina speculatrix* (Sec. 3.6). In the intervening decades considerable progress has been made in developing more sophisticated models such as the "smart bugs" already referred to there. Much of this research has been conducted by neurobiologists who are studying nervous systems to gain an insight into how neurons and neural circuits function in animal life. Although the research is quite specialized, it can cast light on the complexity of what we have referred to above as the physiological state, namely, the neurophysiological processes involved first in the acquisition of sense knowledge and secondly in its use to control behavior.[7]

An act of simple sensation, as already explained (Sec. 4.2), may be seen as occurring in three stages: first is the physical stage, wherein an external stimulus such as light rays impinge on a receptor or organ; then comes the physiological stage, wherein the stimulus introduces an internal modification within the organism; and finally there is the psychic stage, wherein a mental representation is produced in a knowing power. One could say that the earlier robot research has concentrated more on the first stage, whereas what we are about to discuss concentrates more on the second. No claim is made that the third stage, that of knowing in the strict sense, has been reached in any of these modeling attempts, and yet they can be helpful for detailing the substructure required for its ultimate attainment.

The arthropod on which research has more recently been conducted is the American cockroach, *Periplaneta americana*, a large reddish brown roach between one and two inches in length that lives outdoors and indoors, in the latter case typically in dark, heated areas.[8] It is one of

7. The specialized study of the nervous system in the control of behavior is termed neuroetiology; thus it is differentiated from neurophysiology, the study of the nervous system as organic process.

8. Details of this research are provided in Randall D. Beer, Hillel J. Chiel, and Leon S. Stirling, "An Artificial Insect," *American Scientist* 79 (1991), pp. 444–452; see also Randall D. Beer, *Intelligence as Adaptive Behavior: An Experiment in Computational Neuroetiology*, San Diego: Academic Press, 1990.

the most primitive living winged insects and among the oldest fossil insects, dating from the Carboniferous Period and thus over 300 million years old. The model to be discussed is not a physical artifact but is a computer-simulated "insect," appropriately named *Periplaneta computatrix,* which performs in a two-dimensional environment that is pictured on a computer screen. It is equipped with an artificial nervous system and can be programmed to perform a number of tasks. The neuron components of the model are based on characteristics of real neurons: thus their firing frequency is determined not only by inputs from other neurons but also by the neuron's ongoing state and activity. There is also a threshold that has to be reached before the model neuron responds and a saturation point beyond which its response does not increase even though the input may continue to rise. The walking features of this particular computer model have also been duplicated in a six-legged robot, about twenty inches long, which is controlled by a neural circuit identical to that in the computer model, but robotic models have thus far not been constructed for its other behaviors.

All living systems, as seen in the previous chapter, are able to react to changes in their environments so as to preserve their integrity or well being; in this sense all may be seen as stimulus-response systems of the type diagrammed in Fig. 3.6. But plants differ from animals in that the connection there shown between stimulus and response is mediated in a different way. In plants chemical regulators or hormones are secreted within the cells of the plant to effect the response, whereas in animals a more specific and much faster responsive system is also at work, namely, the nervous system. The basic unit of this system is a specialized cell, called the neuron, which serves as a controller between the stimulus and the response, that is, between receptor cells and their associated effector units. The nervous system itself consists in an ensemble of neurons that are interconnected by neural circuits, some of which function in a positive way to activate or excite the neurons to which they are connected, others in a negative way to inhibit their performance.

The basic electrical features of the neural circuits modeled in the artificial insect *Periplaneta computatrix* are shown in Fig. 4.1. The insect is shown schematically, with its main features being a head, which encloses an electronic "brain" and from which extend two long antennae, and a body, from which extend six legs, three on each side. In all there are 78 neurons in the system, though not all are shown individually; these are mediated by 156 connections, not all of which are shown either. Instead the neurons and their connections have been grouped in the figure into subsystems whose function it is to duplicate various aspects

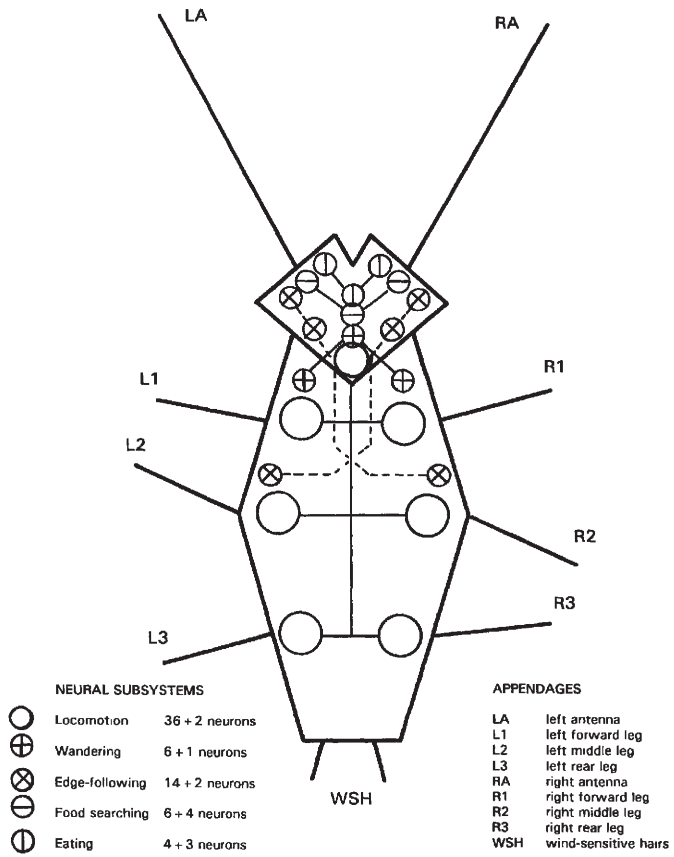

Fig 4.1 Periplaneta computatrix

of the cockroach's behavior. The components of the various subsystems are identified on the diagram by different symbols, as shown, for locomotion, wandering, edge-following, food searching, and eating.

The insect's basic movement is walking, and this is effected by coordinating the backward and forward swings of the legs on each side so that the insect is always supported, at any one time, by having three legs on the ground and still can move at walking gaits ranging from slow to fast. Six neurons are required to effect each leg movement, and these are controlled by two more, for a total of 38 neurons in the locomotion system. These enable the model insect to walk forward in a straight line, but they do not permit its turning to explore its two-dimensional environment. The second control system, that for wandering, effects the turning movement by adjusting the lateral extension of either the left or right front leg; this perturbs the walking control somewhat, but it also causes the insect to turn away from the extended leg. Seven neurons are allotted to this behavior, three for each front leg and one for their control. A yet more sophisticated behavior is one that seems characteristic of roaches, namely, their tendency to wander near an edge such as a wall, often with one of their antennae in contact with the edge. The third subsystem, that which controls edge following, does so by coordinating the information from sensors in the antenna tip on each side with the lateral extensors on that side. Its effect is to maintain the insect's body in a position parallel to the edge. For this eight neurons are required for each side, for a total of sixteen.

Feeding behavior takes up the remainder of the neurons and neural circuits, and this is divided between two additional subsystems, one appetitive, searching for food, the other consummative, eating it. Feeding differs from the locomotive behaviors because it depends as much on the internal state of the insect as it does on its external environment. A number of sensors allow the device to monitor such states: tactile and short-range chemical sensors in the mouth for detecting the proximity of food; longer-range chemical sensors and mechanical sensors on the antennae; and an internal sensor for measuring the level of its energy reserve. When the last-named indicator is low, the artificial insect begins the search for food by comparing the strength of the chemical signals in the two antennae, turning in the direction of the stronger, and homing in on its source. Eating behavior is begun when the insect's mouth signals that food is present; this consists in controlled biting movements that serve to ingest the food. In all, ten neurons control the search for food and seven more its consumption, totaling seventeen for the feeding process.

So as to prevent all of these subsystems from generating incompatible behaviors, priorities are programmed into the insect to organize the various types. The main stimuli derive from the sensory inputs and from the extent of the arousal for food; the behaviors effected from them are arranged in such a way that the action of eating prevents the insect from engaging in other behaviors. These behaviors are then ordered hierarchically as follows: first consummatory, then appetitive, and lastly locomotive or walking, with edge following being the preferred mode and wandering the lowest on the priority list.

Considering that the nervous system of *Periplaneta computatrix* employs only 78 neurons, as compared to the more than fifteen trillion neurons in the human nervous system, it is remarkably sophisticated in its behavior. Yet, from the point of view of sense knowledge, that is, sensation and perception, it provides very little of the physiological apparatus required for their acquisition. For example, there is nothing in the model that duplicates the outer senses of sight or hearing, although optical and acoustical sensors would be relatively easy to add. Considerably more difficulty would attach to providing neural apparatus for inner senses such as imagination, memory, and the instinctive sense. Only a rough attempt to simulate the central sense is provided by the computer apparatus, for all this does is discriminate between the insect's various behaviors and attempt to order them hierarchically. And as far as emotions are concerned, apart from the insect's liking for food, it is difficult even to know what organ simulation would be required to emulate other behaviors, such as that suggesting fear in the presence of danger.

Those developing the model raise questions such as this in their attempt to duplicate what they call the "escape response" of the cockroach. Their attack on this complex behavior begins with the hundreds of "wind-sensitive" hairs on the rear of the roach's body that might be activated by a sudden puff of wind coming from an attacking predator. The problem, as they conceive it, is to have the computer model calculate (in less than 60 milliseconds) the direction of a particular attack from the way these hairs are deflected and then to compute and direct a complex set of leg movements that might enable the insect to escape. From the viewpoint of computational strategy the approach is surely ingenius. Yet it highlights a basic limitation of cognitive science that has already been mentioned (Sec. 4.1), namely, the tendency to formulate problems in ways that are amenable to solution by electronic computers but otherwise disregard the emotional component of the behavior found in living organisms.

4.5 Intellection

The human knowledge process, as has been said, involves sensation, perception, and, over and beyond these, intellection, a process never found without the first two. Intellection is commonly regarded as the knowledge process that serves to differentiate humans from the lower animals—the source from which their language, literature, culture, science, and other distinctively human accomplishments derive. The simplest way to characterize intellectual knowledge is to say that it is concerned with meaning or content, that it grasps ideas or concepts that transcend the level of sense knowledge, that is, the levels of both sensation and perception. Sensation gives a person knowledge of concrete aspects or qualities of individual, material objects, e.g., colors, sounds, and odors, and when such qualities are organized so as to constitute a unity in space and time, the result is a perception, e.g., of this individual tree. Apart from these instances of sense knowledge, a person can also say, "That is a tree," and this is an example of intellection or of intellectual knowing. The statement implies that the one making it has a concept of tree, that is, knowledge of tree that is universal and so transcends any instantiation of it. Even though the term "tree" is being applied only to a particular oak, it can be applied to innumerable other trees, and in this sense it is universal. To affirm of an object that it is a tree is to make a judgment, to state that the objective reality is constituted as it is understood by the knower. The power or faculty that enables a human to make such a statement is called the intellect.

In a previous section the expression "this apple, large, red, and sweet" was used to designate a percept. Whereas that particular percept puts the knower in contact with "this apple," the power of intellect enables him or her to extract from the percept its intelligible content, the meaning of "apple" in general, what might be called "appleness." Neither of these English words is actually the meaning referred to, for the intelligible content can be translated into different languages, using appropriate terms in those languages to make that meaning understood in them. The percept as expressed in this way is obviously a rich source from which a variety of concepts can be formed. Thus a person can grasp from the "this apple" percept the concept of apple, but also the concepts of large, red, and sweet, as indicated, plus others not mentioned, such as juicy and fragrant. Each such concept has an element of universality associated with it, in the sense already noted that the one who formulates the concept is able to apply it to another object met in experience and say of it, for example, "That also is red." The concept, precisely as abstracted from the percept, is itself abstract; as applicable to other perceived objects in unlimited number it is also universal. Thus, whereas the percept is concrete and individual, the concept is abstract and universal, the root source of generalizations the knower is able to make once in possession of it.

The process by which concepts or ideas are formed from sense knowledge is usually explained in terms of a special intellective function known as abstraction. The ability to abstract is a sign that the intellect itself is not purely passive in forming the idea but exercises an active role also. The active power of the intellect is designated by a special name, the creative or agent intellect (Lat. *intellectus agens*), and its passive power is correspondingly denominated the receptive or possible in-

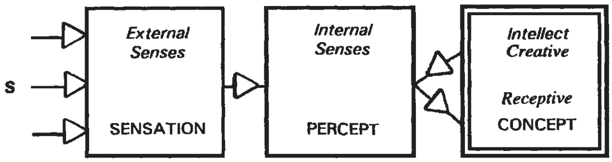

Fig. 4.2 Concept Formation

tellect (Lat. *intellectus possibilis*). Through sense knowledge, as just explained, the knower is in possession of the percept of a concrete, material object. By its own natural light (Lat. *lumen naturale*), the agent intellect illuminates this percept and extracts or abstracts from it various meanings or contents that are latent within the object perceived, leaving aside all the individuating notes that characterize the object in its singularity. This process results in one or more new intentional forms or intelligible species (Lat. *species intelligibiles*), which the creative intellect impresses on the receptive intellect, and so gives rise there to corresponding abstract, universal concepts through which the object can be understood. The termination of this process, the concept, is called such because it is the result of a vital operation whereby it is actually conceived (from the Lat. *conceptus*), or given birth to, within the receptive intellect, once the knower has achieved understanding of the object presented in sense experience.

This process of concept formation, referred to by some as ideogenesis or the birth of ideas, is diagrammed in Fig. 4.2. The figure shows in a schematic way the interrelationships between sensations, percepts, and concepts as these are produced by the external senses, the internal senses, and the intellect respectively. This schema is not to be viewed as sharply separating the work of the intellect from that of the senses. The substantial unity of the human knower implies not only the unity of organ functioning but also that of sense and intellect. As the soul is to the body, so the intellect is to the senses. The body never acts without being animated by the soul, and similarly, in human beings when knowing, the senses do not act without being animated by the intellect. This implies that the intellect is already at work with the inner senses in the formation of the percept. Indeed, the intellect prompts this formation so that it will be able to derive from the percept the intelligible content latent within the object sensed.

In Sec. 4.1 knowledge was defined as the intentional presence of an object in a subject, and this definition can now be seen to be verified at each stage of the processes diagrammed in Fig. 4.2. Sensation is knowing at the basic level, since it consists in the reception of a form in the knower. Thus green is sensed in the eye when the eye is presented with a properly illuminated green object, say, grass, and electromagnetic radiation of the corresponding wavelength impinges on the retina, producing there the sensation of "green." Perception is also an instance of sense knowledge, though more elaborated, since it consists in the presence within the internal senses of an image or likeness of the object perceived. Thus "this blade of green grass" is known when the individual sensations of the outer senses are integrated by the central or common sense. The intentional form there produced, the percept, grasps the object in a unified way with all its singular and distinctive attributes. Conceptualization is likewise knowledge, now at the intellectual level, since it consists in the presence within the intellect of one or more ideas or concepts that express the whatness or essential content of what has been apprehended. The intentional form or mental representation produced at this level obviously can be manifold: "grass" as instantiated in this blade of grass, but as applicable to any other grass the knower may encounter; "green" as seen there, but as applicable to other objects of the same color, and so on.

Before investigating in detail the various types of concepts that can be produced by the intellect, we must complete the schematic diagram of Fig. 4.2 to show the appetitive power that is the correlate of the intellect in humans, namely, the will. This can be done simply by upgrading the animal powers represented in Fig. 3.9 by adding the two distinctively

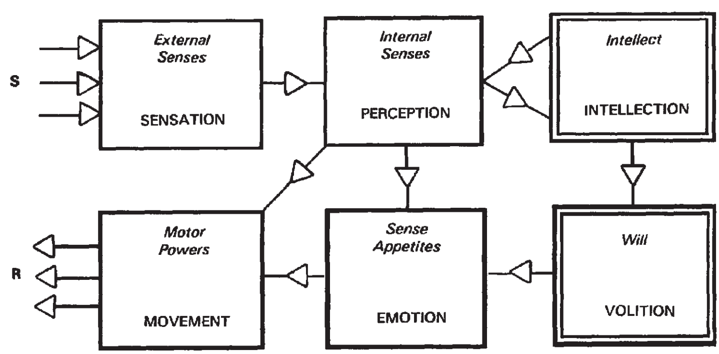

Fig. 4.3 Human Cognitive and Appetitive Powers

human powers, intellect as the cognitive power whose activity is intellection and will as the appetitive power whose activity is volition. The resulting human powers are diagrammed in Fig. 4.3, with the intellect and the will boxes in double outline to emphasize their human status. Along the top line, the cognitive or receptor line, are shown from left to right the powers of sensation, perception, and intellection; along the bottom, the appetitive or activator line, are shown in the reverse order the powers of volition, emotion, and movement. Precisely how these powers work together to produce the distinctively human act will be discussed below in Sec. 5.5.

4.6 Basic Types of Concepts

It has been noted that the intellect is able to form a wide variety of concepts, but the problem of their typology has yet to be addressed. One way of classifying them is in terms of the process whereby the intellect forms its concepts, already identified as abstraction and in Fig. 4.2 represented by the broken line connecting the box for intellect with that for the internal senses. To abstract is to pull out, or to extract, one or another intelligible content or meaning that can be seen to be contained in a percept, leaving aside everything else that may be present in it. This abstractive process yields various degrees of abstractness depending on how much the intellect leaves aside the concrete and individual aspects contained in the percepts it considers. Three orders or degrees of abstraction are commonly enumerated, and these suffice to distinguish concepts into three types, namely, natural or physical concepts, mathematical concepts, and metaphysical concepts, each of which will now be explained.

Consider the percepts represented by such expressions as "this yellow sulphur" and "this lead ball," and then the concepts that may be formed from them. Sulphur and lead are natural or physical objects that exist outside the mind, and so the concepts formed to understand them may be spoken of as natural or physical concepts. Examples related to the sulphur would be "sulphur," "yellow," or "element"; those related to the lead, "lead," "heavy," or "cold." What one does when one forms concepts such as these is leave aside all of the individual characteristics associated with the "this" of the percept and grasp a meaning that is common to all classes of objects that share these properties. The concepts formed all imply some reference to sensible matter, that is, to matter that directly or indirectly falls under the senses, but they abstract from or leave aside individual or singular attributes. The resulting type of abstraction from matter is referred to as physical abstraction, and it is used in all of the natural sciences as well as in ordinary discourse.

Mathematical concepts are more abstract than physical concepts for the simple reason that more matter is left aside when the former are grasped by the intellect than when the latter are so grasped. Consider, for example, the perceptual basis represented by the expressions "this lead ball" and "these five crystals of sulphur," and then the concepts of "sphere" and "five" that may be abstracted from the ball and the number of crystals respectively. "Sphere" and "five" are mathematical concepts; they do not refer exclusively to any individual sphere or group of five, but rather to all classes of objects that share that geometrical shape or number. Neither do they contain any reference to sensible matter, in the sense that "sphere" of and by itself does not connote that the object is made of lead or of wood, but merely that it is composed of continuous quantity, an imaginable "matter" made of pure extension, not one that has the sensible qualities associated with lead or wood. Similarly the concept "five" contains no reference to the sensible objects from which it is abstracted, and it too is composed of units that are only imaginable. Because of its greater abstractness one could say that "sphere" is more intelligible than "ball" in the sense that it leaves aside all the imperfections usually associated with sensible matter. It can thus be conceptualized as perfectly fulfilling the definition that every point on its surface is at exactly the same distance from its center—something that would not be true of a ball made of lead or wood. In this way of looking at things, mathematical concepts are more intelligible than physical concepts insofar as they are more removed from sensible matter, which is a source of contingency and even imperfection when compared to pure quantitative extension.[9]

Metaphysical concepts, finally, have more in common with mathematical than with physical concepts, since they are the most abstract of all. They are usually spoken of as being separated from matter entirely, i.e., as not including any reference whatever to sensible or even to intelligible matter. Examples of such concepts would be "being," "sub-

9. For a fuller elaboration of the philosophy of mathematics behind these statements, see Hippocrates G. Apostle, *Mathematics as a Science of Quantities*, ed. A. M. Adelberg and E. A. Dobbs, Grinnell, Iowa: The Peripatetic Press, 1991, as well as Apostle's earlier "Aristotle's Theory of Mathematics," *Journal of Hellenic Philosophy* (Athens, Greece), 1978–1979, pp. 154–212, and his *Aristotle's Philosophy of Mathematics*, Chicago: University of Chicago Press, 1952. Also relevant to this study are his translations of and commentaries on Aristotle's *Physics* (1969, 1980) and Aristotle's *Posterior Analytics* (1981), both available from the Peripatetic Press.

stance," and "existent." Such concepts express an intelligible content that is found in sulphur and lead, since both of these are beings and substances, and both are existents in the extramental sense and in the mental sense as well. Metaphysical concepts, so characterized, are obviously very general and can apply across the entire range of beings, even to things that are immaterial and incorporeal, should such exist, and to logical entities also.[10] Little need be said about them here, since philosophy of nature is concerned mainly with physical and mathematical concepts. Yet they do serve our purposes by illustrating how concepts of various types can be distinguished on the basis of their abstractness or degree of separation from the matter that is directly perceived in sense experience.

All three types of concepts, it should be stressed, are the product of intellectual activity, and as such they exist in the intellect or in the mind. The objects they represent, moreover, exist outside the knower or outside the mind. Granted that the mode of existence of the object outside the mind is different from the intentional existence of its mental representation or concept in the mind, there is still a correspondence or equivalence between them. It is on this basis that all the concepts discussed so far can be regarded as *real* concepts. They are real in the sense that, though they exist in the mind, their content also exists in some way outside the mind. This point is of extreme importance for developing a realist philosophy of science. For purposes of such a philosophy, "real" when applied to intellectual knowledge always has a twofold reference: it refers to something that, as known, exists in the intellect, and that, as extramental, also exists outside the intellect.

Having defined knowledge as the intentional presence of an object in a subject, and real concepts as representations in the mind of forms that exist outside the mind, the question arises whether there can be any concepts that are not real in this sense. The common answer to this is affirmative, because it is possible for the intellect to formulate concepts that have no direct extramental reference but that serve a useful purpose in putting order into the concepts that do. This second broad class of concepts are spoken of as *logical* concepts. One might say that such concepts designate beings or entities that exist in the mind, and for this reason they can be referred to as beings of reason (Lat. *entia rationis*). They may also be thought of as having an intentional character, since they have an intentional mode of existence that is similar to that of real concepts. To differentiate them from the latter they are called "second in-

10. For a brief introduction to metaphysical reasoning as employed in this study, see Sec. 5.8 below.

tentions" and real concepts are spoken of as "first intentions." This terminology will be explained more fully in the section following on intentionality, but for now a second intention is said to be "second" simply because it is based on a first intention, or builds on a first intention, usually by indicating some way in which the real concept is related to other concepts.

Some examples may suffice to clarify this difference between real concepts, which stand for or represent entities that exist outside the mind, and logical concepts, which designate entities whose only existence is in the mind. Consider the statement "Sulphur is yellow" and compare it with the statements about it such as "Sulphur is a *subject*" and "Yellow is a *predicate*." We have already given reasons for holding that "sulphur" and "yellow" are real concepts; now we point to "*subject*" and "*predicate*" as examples of logical concepts. To say "Sulphur is a *subject*" is to say nothing about sulphur as it exists extramentally, but it is to say something about how it is related to the concept "yellow" when the mind forms the proposition "Sulphur is yellow." The term "*subject*" thus represents a logical concept. Another example: suppose one wishes to take the statement "All sulphur is yellow" and reverse the order of the subject and predicate while still preserving the truth of the statement. One can do this by converting the "*All* sulphur is yellow" into the statement "*Some* yellow is sulphur." The *all* and the *some* one then uses are logical concepts; the mind makes them up so as to modify or quantify its real concepts and preserve a true relationship between them when their positions within a proposition are interchanged.

Again, consider the statements "Man is an animal" and "Man is a *species*," meaning by *species* a class containing individuals that are only numerically distinct; or "Animal is a sentient organism" and "Animal is a *genus*," meaning by *genus* a class containing things different in kind as well as numerically distinct from each other. Here *species* and *genus* are logical concepts, for although men and animals exist extramentally, *species* and *genus* have essentially the same character as *subject* and *predicate*: they tell us how such concepts as "man" and "animal" are related to other concepts without telling us anything about a man or an animal in its extramental existence.

More sophisticated examples can be taken from any logic textbook, most of whose technical terms stand for logical concepts. Of particular interest are concepts of this type that explain how propositions, rather than concepts or terms, stand in relation to one another. For example, one may consider the complex statement, "This is lead *and* this is heavy." The *and* here is a logical concept that connects the two propositions making up the complex statement. An important concern of logicians is how to define the truth and falsity of a compound proposition of this type in terms of the truth and falsity of the components that make it up. Such a compound proposition can also be written in the form "*p and q*," where *p* stands for the first component, *q* for the second, and *and* for the relation that obtains between them. Logicians define characteristics of this relation, called conjunction, that are independent of the contents of the propositions *p* and *q* and are a function only of their truth and falsity.

Another complex proposition that assumes importance in what follows is the statement, "*If* this is lead, *then* this is heavy; *and* this is lead; *therefore* this is heavy." Here the italicized terms, *if, then, and,* and *therefore*, as previously, all designate logical concepts. One can again use the variable *p* to stand for the statement "This is lead" and another variable *q* to stand for the statement "This is heavy." Then one can reformulate the complex statement just given as:

If p, then q; and p; therefore q

This is a logical statement, all of whose terms stand for logical concepts or variables and whose verification pertains to the science of logic.

The various types of concepts discussed to this point may now be tabulated as in Fig. 4.4. All of the entries to the left of the vertical double line pertain to the perceptual order and so designate extramental objects perceived by the senses, as schematized in the two boxes to the left side of Fig. 4.2; all of the entries to the right of the double line, on the other hand, represent concepts, and thus they refer to the contents of the box labeled intellect on the right of the same figure. Concepts between the vertical double line and the vertical single line to its right are real concepts, whereas those to the right of the vertical single line are logical concepts. Real concepts are further subdivided into physical, mathematical, and metaphysical, as indicated, with the progression from top to bottom being in the order of greater abstraction from matter.[11]

4.7 Intentionality

With the general outlines of a model for the study of mind now in place, we turn to the epistemological problem and consider how this model can be employed to justify a realist theory of knowledge wherein

11. A fuller typology of concepts, including those more characteristic of modern science, is given in Fig. 7.1 of Sec. 7.5 below.

Types of Concepts—I

OUTSIDE MIND	INSIDE MIND	
Percepts	**Real Concepts**	**Logical Concepts**
	PHYSICAL	
this	sulphur	*subject*
yellow	yellow	*predicate*
sulphur	element	
this	lead	*all*
lead	heavy	*some*
ball	cold	
	MATHEMATICAL	*genus*
		species
	sphere	
	five	
		p and q
	METAPHYSICAL	
	being	*if p, then q;*
	substance	*and p;*
	existent	*therefore, q*

Fig. 4.4 Basic Types of Concepts

claims can be made for the truth and certitude of statements about the world of nature. The strategy employed will be to show that it is possible to be assured of the reality of objects of ordinary experience, and also of truth claims made about them in practical affairs as well as in the elaboration of a philosophy of nature. Using this foundation we shall then be able to delineate the problems that are specific to modern science, with its techniques of measurement and theoretical construction, whose solution will be addressed in the second part of this volume.

The notion of intentionality has thus far been employed in speaking about mental representations and the type of presence they have in the knowing subject—an intentional or immaterial presence as opposed to a material presence. To delve further into this notion it is helpful to consider the term "intention" and how it has come to be associated with a theory of knowledge, as in the expressions "first intention" and "second intention" introduced in the preceding section. As commonly employed, it seems obvious that an intention can be applied more readily to the will than it can to a knowing power such as the intellect. Yet there are similarities between the operations of appetitive powers and cognitive powers, and so the application that is more known can cast light on the one that is less so.

The word "intend" means a tending or a tendency or an inclination toward something, and thus it implies a twofold reference. The first is to the subject in which the tending is found (the "tend" part), the second to the object toward which the tending is directed, the something that is intended (the "in-" part). Thus, like the knowledge of which they are a part, intentions have both a subjective and an objective aspect: they are in a subject and they are directed toward an object. As applied to an appetitive power such as the will, an intention might mean the internal act by which the will tends toward something desirable, and then it is the same as the act of willing it or wanting it. At other times it might mean the object toward which the will tends, usually an external entity or activity or outcome that appeals to the person willing and so elicits this act from his or her will. So understood the word refers properly to the act, improperly, by metonymy, to the thing intended.

When the term intention is transferred to a cognitive power such as the intellect, it can take on a variety of meanings. First it properly designates the knowledge or the act of knowing whereby the intellect is brought to bear on the thing known. Secondarily and improperly it is used for the thing known, analogous to the thing willed in the case of the will. But here the application becomes a bit more complicated, because, in the case of a knowing power such as the intellect, the thing is known through a mental representation, a concept or similitude of the object known, as already explained (Sec. 4.5). In view of the fact that the concept stands in for the object known, the concept or representation is called an intention also. Still more complexity is introduced by the peculiar ability of the intellect to reflect on its own thinking and to form, as it were, concepts of its concepts. To account for this feature of intellection a distinction is introduced between concepts that represent extramental objects, called real concepts or first intentions, and those that represent mental representations alone, called "beings of reason" or logical concepts or second intentions, as detailed in the preceding section. This is the general setting in which the problem of intentionality in knowledge should be located, and where, more specifically, the problem of epistemological realism must be addressed.

As a first step in this project it is helpful to set aside for the moment the epistemological status of logical concepts or second intentions and consider how first intentions are formed by the intellect and how they enable the knower to make claims about the real world. Let us consider the simple case in which a knower makes the judgment in the expression "Sulphur is yellow." To locate the expression in its proper context, let us further assume that the knower is equipped with the powers shown in Fig. 4.3 and that these operate naturally to make of the knower a common-sense realist. The epistemology behind that realism supposes that a world of nature exists independently of the knower's thinking about it, that objects and events are real, that as presented in sense experience they can be known, and that the natural light of the intellect is adequate to the task of knowing them as they are.

Making a statement of the above kind about sulphur implies that the knower's intellect has the natural ability to know and understand such an object as it is presented in sense experience. Sulphur and similar objects are real and have natures, and as directly known these natures become intentions, what we have called first intentions. The natures are real and they exist in the objects whose natures they are. As simply existent such natures are not intentions, but as known they become intentions, that is, when they are grasped and understood by a knowing intellect. The grasping and understanding in this type of knowing is the act of conceptualizing, and the first intention that is here conceptualized is that of sulphur. Because the nature of sulphur is real, the concept whereby sulphur is grasped may be called real also. But here we have to be careful, for like all intentions the concept may be looked at in two ways, either as the act of the one conceptualizing and the representation it produces in the intellect, what we shall now call the *formal* concept, or as the object thus conceptualized, what we shall now call the *objective* concept. The formal concept or the formal first intention is real only in the sense that the psychological act of conceptualizing and the representation it produces are real modifications in the one knowing.[12] The objective concept or the objective first intention is real in another sense also, for as a first intention it is more than an activity and modification in the mind of the knower. It is something in the sulphur also, since this is what is known, more precisely, the nature of sulphur. In virtue of the object's being the nature of sulphur, knowers can say that they *know* the sulphur as a real, extramental, or mind-independent being. On this accounting, individu-

12. It is this formal concept that is retained in the intellectual memory and is available for recall whenever the knower returns to a consideration of the object conceptualized.

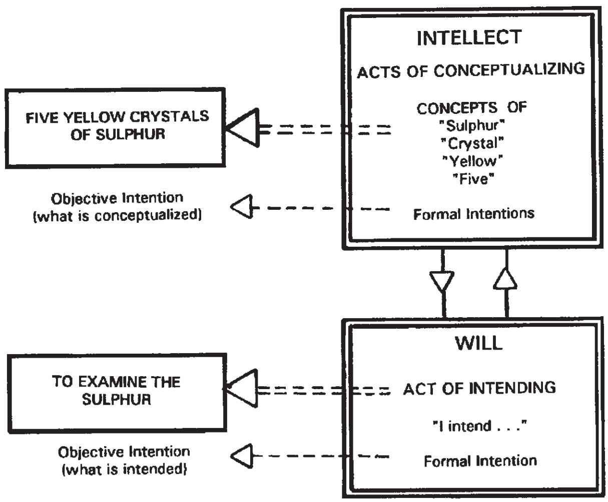

Fig. 4.5 Intentions of Intellect and Will

als do not know the concept of sulphur, but rather, *through* the concept, they know the sulphur, and this is what ultimately grounds their ontological claim.

To expand the analysis further, let us suppose that the object of the knower's consideration is now a percept that is the referent of the expression "five yellow sulphur crystals." To make a statement such as "Sulphur is yellow," the knower, in addition to having conceptualized sulphur, would also have had to conceptualize yellow. Additional statements would require the further conceptualization of five and crystal. The resulting series of concepts are shown in Fig. 4.5, which diagrams various intentions of the intellect and the will, where the concepts appear in the box labeled intellect. This figure builds on the content of Fig. 4.3, now with all the various cognitive and appetitive powers of the human soul blocked out except the intellect and the will. The contents of the intellect box are situated in the portion of the intellect box that has been called the receptive intellect in Sec. 4.2, for this is where concepts are generated through the action of the active intellect on the percepts of sense experience. Opposite the intellect box is shown the object of its consideration on the left, and directly below it the box labeled will, with its corresponding object to the left of it also.

In view of the fact that intentions can more readily be seen as acts of the will than as acts of the intellect, the lower part of Fig. 4.5 should be considered first. The diagram assumes that a person, the knower, is intent on examining or considering a sample of sulphur given in sense experience to ascertain what might be said about it. The formal intention is the act of intending in the will, represented by the words "I intend . . . ," and the objective intention is simply what one intends, shown on the left in the box labeled "to examine the sulphur." Thus a will intention has the twofold aspect as already explained: a subjective aspect, the act of willing (the formal intention), and an objective aspect, what is intended (the objective intention).

These formal and objective aspects have counterparts in the intellect when one knows the sulphur one intends to consider. Assuming that the sulphur is sensed through the percept whose referent has been described as "five yellow sulphur crystals," this is grasped intellectually through a series of concepts, which are in turn signified by the terms "sulphur," "crystal," "yellow," and "five." The terms designate first intentions, acts of conceptualizing and representations that are real entities existing in the mind of the knower and so are real concepts in the sense of formal intentions. One could not formulate these intentions, however, if one did not have corresponding objects to conceptualize, and these are shown on the left in the box labeled "five yellow sulphur crystals." Each of these is an objective intention, and each of these is real if the knower has sensed and perceived properly, namely, if the crystals really are sulphur, yellow in color and five in number. On the basis of these objective intentions the knower can formulate the complex expressions "Yellow sulphur" and "five crystals," or alternatively, the propositions "Sulphur is yellow" and "There are five crystals." Although these expressions and propositions are formed in the mind or intellect, they are expressions and propositions about the real world. The sulphur, its crystalline state, its color, and the number of crystals are objective first intentions and as such they are real, extramental, and mind-independent.

To grasp the significance of these statements, the real concepts mentioned in them should now be juxtaposed to the logical concepts explained above in Sec. 4.6. To make clear the difference between the latter concepts and real concepts, we present in Fig. 4.6 the upper part of Fig. 4.5, now redrawn so as to include second intentions, called rational or logical or mind-dependent concepts to differentiate them from the real, in the sense that real is being used here. Having the real concepts of sulphur, yellow, crystal, and five, one may make the judgments that sulphur is yellow and that there are five crystals. On the basis of these statements additional judgments may be made such as those analyzed above

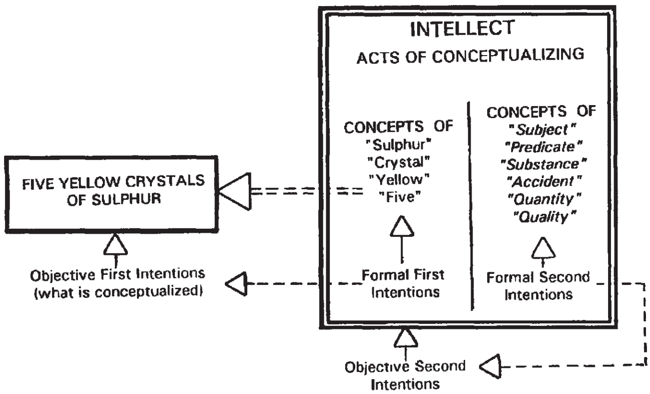

Fig. 4.6 First and Second Intentions

in Sec. 4.6, namely, that sulphur is a *subject* and yellow is a *predicate* in the statement, "Sulphur is yellow." The concepts of *subject* and *predicate* here are second intentions; they are concepts built on concepts, in this case showing how the concepts of sulphur and yellow are related to each other when placed in this particular statement. Unlike real beings, *subjects* and *predicates* exist only in the mind. Having no existence outside the mind they are said to be mind-dependent, that is, solely dependent on the mind for their existence. Real beings, on the other hand, are mind-independent, for while they exist in the mind as first intentions when conceptualized, they also exist outside the mind as objective intentions when the entities they represent are actually known.[13]

Other second intentions are signified in the right-hand column of Fig. 4.6 by the words "*substance*," "*accident*," "*quality*," and "*quantity*." These terms can be used to form propositions such as "Sulphur is a *substance*" and "Yellow is an *accident*," or "Yellow is a *quality*" and "Five is a *quantity*." Like "*subject*" and "*predicate*," all of these predicate terms, when conceptualized, are formal second intentions. Their correlates, what is conceptualized, are objective second intentions, and these turn out to be quite different from objective first intentions or real be-

13. The expressions "mind-dependent" and "mind-independent" have been proposed by John Deely as well suited to convey the sense intended by the Latin expressions *ens rationis* and *ens reale* respectively. See his *Tractatus de signis: The Semiotic of John Poinsot*, Berkeley: University of California Press, 1985, 548–551.

ings. The difference is diagrammed in the lower right-hand part of Fig. 4.6. When a formal second intention is conceptualized its direct referent is not an extramental reality but rather a formal first intention as this exists in the mind of the knower. Statements that involve second intentions are thus not statements about the real world. They are statements about a statement and so involve entities that are mind-dependent or simply beings of reason. Such second-level concepts are logical entities, and as such they are the principal objects of consideration in the science of logic.

4.8 Intelligibles and Sensibles

Earlier in this chapter we referred to the objects of sense knowledge, that is, of sensation and perception, as sensibles or *sensibilia*, meaning by this what can be sensed (Secs. 4.2 and 4.3). The corresponding term for objects of the intellect is intelligibles or *intelligibilia*, meaning by this what can be grasped or understood by the mind or intellect. Both intelligibles and sensibles, as objects of intellectual knowledge and sense knowledge respectively, are objective first intentions in the sense in which that expression has been used in the previous section. Because such intentions plays an important role in a realist epistemology, and since they are intimately related to the natures discussed in previous chapters of this study, some reflections on their ontological status may prove helpful at this point.

In the natural sciences as in ordinary discourse the primary intelligibles are the natures of material objects as these are perceived in sense experience. Such natures are the starting points for discourse about the world of nature. They are unproblematic, in the sense that they are built into the language people use to refer to objects of which they have experiential knowledge. When individuals use a substantive term correctly, say, "horse" or "oak" or "lead," this is an indication that they have grasped the nature to which that term corresponds. They grasp it in the act of forming the concept the term signifies, in other words, by a formal first intention. The nature they grasp in this conceptualizing is an objective first intention. It enables them to make such statements as "That is a horse," or "This tree is an oak," or "That ball is made of lead." Concept formation of this type takes place naturally in intelligent beings: no more personal effort is required for conceptualizing than is required for breathing or digesting one's food. Through the concepts humans form in this way they come to know natures spontaneously and automatically. It is by means of such natures that they are put in epistemic contact with a real, extramental world.[14]

As was pointed out at the beginning of Chap. 1, however, the intelligible aspects of things are not exhausted by this basic grasp of their inner dimension that was there identified with nature. People do not achieve distinct and comprehensive knowledge of a nature the first time they encounter it in experience. Rather they grasp it in a general and indeterminate way that is always open to further development and refinement. How this fuller understanding of natures comes about has been the burden of the discussion in the preceding three chapters. There the point was made that the primitive knowledge of a nature is effected through a natural form (NF) that is the intelligible correlate of a co-principle that is itself refractory to understanding, namely, protomatter (PM). Such a natural form in its specifying and stabilizing and unifying functions alone may be thought of as represented by the letters NF in Fig. 1.3. A better grasp of the nature or natural form is obtained when consideration is narrowed down to the forms of inorganic substances and of organisms in the plant and animal kingdoms, as in the previous two chapters. Now, a generic powers model of an inorganic nature has been provided above in Fig. 2.6, that for a plant nature in Fig. 3.5, and that for an animal nature in Fig. 3.10. But none of these, as has been insisted on in previous chapters, is a model for a specific nature. To be fully understood, the generic model has to be associated with an individual of a particular species, say, with this sulphur or lead, or with that geranium or oak, or with that squirrel or horse. When this is done one obtains a powers model of the nature or natural form that is the object of the mind's consideration, the objective first intention that terminates its knowledge act, as diagrammed in Figs. 4.5 and 4.6.

The objective first intention puts the knower in direct contact with a nature in the real world, an extramental reality, whereas the formal first intention is a mental representation, an act of conceptualizing in the mind of the knower, the intentional means whereby one is able to grasp this object of thought. Again the point has to be made that the knower does not know the concept, but rather, through the concept, knows the nature as object. Thus the definition of knowledge given in Sec. 4.1 is

14. The concepts thus referred to are obviously those of a normal observation language. The scientific concepts to be discussed in Secs. 7.1 and 7.2 below, namely, metrical concepts and theoretical concepts, build on these natural concepts and thus involve elements of construction that are usually not found in ordinary discourse.

fulfilled: the intentional presence of an object in a knowing subject. The object in the case of intellectual knowledge is the intelligible, the objective first intention in the order of intellect, and the mind's activation by that intelligible is the knowledge act and its product, the formal first intention in the order of intellect, otherwise known as the concept.

The foregoing analysis of formal and objective intentions may be carried out also for the two types of sense knowledge, sensation and perception. Indeed, this additional analysis becomes necessary if one is to uphold the case for realism, for the assumption on which the first analysis is based is that the outer and inner senses sense and perceive respectively their objects as these exist in the real world. Apart from intelligibles, therefore, sensibles have to be considered to show how they are the objects of the outer and inner senses. When this is explained, all three of the cognitive powers shown in Fig. 4.3 will have been reviewed for their epistemological import. Sensibles, of course, have already been introduced in the discussion of sensation and perception in Secs. 4.2 and 4.3 above, but there still remains an important problem concerning them that has to be addressed.

Just as the objective intention in the order of intellect is the intelligible and the formal intention in the same order is the concept produced by the act of conceptualizing, parallel pairs of intentions can be identified that function in both sensation and perception. The only difference is that it is not necessary to distinguish first and second intentions in sense knowledge, since this distinction is peculiar to intellection or to concept formation as this has been explained in Sec. 4.5 above. In knowledge obtained by the outer senses, the objective intention is the proper sensible that activates the particular outer sense, for example, color, sound, or other sensible quality, and the formal intention is the sensation or the act of sensing whereby that color, sound, or other sensible quality is actually sensed. In knowledge obtained by the inner senses, on the other hand, the objective intention is a common sensible or a complex of sensible qualities that is gleaned from more than one external sense, and the formal intention is the percept or the act of perceiving whereby such a complex object is rendered present to or perceived by the knower.

In both of these cases the problem posed relates not to the subjective side of the sensing or perceiving process, the formal intention, but rather to what is sensed or perceived, the objective intention. Those who hold for the subjectivity of sensible qualities maintain that such qualities have no existence independently of the sensing subject, and on this ground effectively deny the very existence of objective intentions for such qualities. They find convincing Galileo's example of the movement of a feather across the skin to explain the tickle. So they introduce a distinction between primary qualities such as movement and secondary qualities such as the sensed tickle, and hold that the primary qualities have objective existence whereas secondary qualities do not. As a result they populate the universe with particles in motion and attempt to explain all sensations by the various kinds of movement these particles undergo, meanwhile denuding the objective world of sensible qualities in their traditional understanding.

The source of the difficulty here is an improper grasp of the role of the mental representation in the knowledge act. To think of the concept as *what* is known, rather than seeing that the nature is what is known, though *by means of* the concept, is to cut oneself off from intellectual knowledge of the real, for one is always left wondering about any extramental reality to which the concept might correspond. Similarly, to think of the sensation or the percept as itself *what* is known, rather than seeing the sensible quality as what is known, though *by means of* the sensation or percept, is to be imprisoned within one's sense organs and brain. The result is a radical solipsism that prohibits individuals from ever making statements about the objects of experience, leaving them to dwell in a world of their own imaginings.

The tickle may be something sensed on the surface of the skin, but that admission surely does not permit the inference that there is no movement there, or extending the argument further to hold that there is no heat in boiling water, no color in a ruby or a rose, no sound in the cry of a bird, or no odor or taste in an onion. All of these are accidents or accidental modifications of the subjects in which they are sensed. Just as those subjects have natures (inorganic, plant, or animal in kind), so accidents may be said to have natures in an analogous sense. And even if we cannot know *precisely* the nature of heat, of color, and so on, we can at least *model* those natures in terms of the modalities they introduce in the components of the substantial natures in which they exist, namely, the electrons, atoms, and molecules of which we have discoursed in previous chapters.[15] Such modalities, the subject of ongoing investigations in thermodynamics, optics, acoustics, and organic chemistry, *are* the objective intentions, the objects that are grasped when one senses and perceives qualities such as these. The fact that molecular vibrations may seem quite unlike the sensations of heat and sound is not relevant here; the important point is that the sensations are the means by which the vi-

15. How this can be done is discussed below in Sec. 10.7.

brations are discovered. The senses do not judge, they merely report the presence of their stimulation, leaving it for the intellect to judge what there is in nature that ultimately stimulates them.

4.9 Truth: Active and Passive

The definition of knowledge that has been explained thus far provides a foundation for understanding what is meant by truth. Truth may be defined as the conformity between the object as it exists outside the knower and the intention that represents this object to the knowing subject, or, more simply, it is the correspondence between the object known and the knowing subject. The possibility of attaining truth in this sense rests on the proper functioning of the senses and presumes that these are healthy and free from organic defects such as color blindness. What a normal person calls green is the color green as this exists in a green object such as grass. Likewise, when individuals apprehend grass in the sense of knowing what grass is, as instantiated in the object before them, they have the basic information for making truthful statements about grass in their subsequent discourse.

A fuller understanding of the notion of truth requires that we expand somewhat on what has already been said about intellection (Sec. 4.5). Thus far in treating of the intellect we have considered only the first act whereby it forms concepts and so attains a knowledge of natures in the physical world. Apart from the act of conceptualizing, there are two other acts that take place in the intellect, the act of judging and the act of reasoning. The second act of the mind, judging, is the act of combining concepts to form meaningful statements, as just seen in the expression "Grass is green." Here the intellect juxtaposes "grass" and "green," decides that the two go together, and so proceeds to affirm "green" of "grass." The third act of the mind, reasoning, goes beyond this, for it uses the products of judgment to yield yet further meaningful statements. It is the act of discoursing from two or more statements to conclusions that are entailed by them. An example would be the complex expression "Chlorophyll is green; grass contains chlorophyll; therefore, grass is green." Here, assuming the truth of the component statements, the intellect juxtaposes the first two propositions ("Chlorphyll is green" and "Grass contains chlorophyll"), decides whether or not they entail a valid consequence, and if they do, proceeds to draw from them a third proposition, namely, the conclusion they imply, "Grass is green." Most scientific activity is concerned with how to proceed in the last two operations of the intellect so as to avoid error and attain truth.

Since truth in its most general sense is the conformity of knowledge with its object, it is possible to apply truth to any form of knowledge, including sensation, perception, and conceptualization, insofar as they are in genuine conformity with their respective objects. These three forms of knowledge, however, are special, since they are the basic means through which all other knowledge is acquired. The actual impinging of an object on the external senses is the ultimate grounding of human knowing, for people either contact reality through the senses or they never contact it at all. Because of this, the lack of any one of the senses deprives the knower of all the knowledge that particular sense might have apprehended. If individuals sense, assuming a normal state of the sense organ and the absence of other aberrations, they sense something; and if they sense something, they sense it as it is. The same applies to perception: assuming proper function of the nervous system and the brain, if individuals perceive, they perceive something, and if they perceive something, they perceive it as it is. Yet again, if an object is properly sensed and perceived, the intellect naturally and spontaneously grasps its intelligible content and formulates this in the concept, grasping its nature as it is.

The sensation, the percept, and the concept are all examples of what may be called *apprehensive* knowledge. The validity of this type of knowledge, as explained in the previous section, is assured by the necessary relationships that obtain between the cognitive powers and their respective objects. Truth at this level is natural and unavoidable; it is built into the cognitive powers themselves, which enliven the knowing process in the same way the human form enlivens the healthy body to unerringly perform its life functions. But this type of truth, known as passive truth or material truth, even though naturally guaranteed, does not have salient features of the truth found in another type of knowledge, *judicative* knowledge, that produced by the second and third acts of the intellect.

Truth in its full significance and in an active and formal sense is first found in the second act of the mind, the judgment. To understand this one must recognize that in apprehension the mind grasps only bits and pieces of the real. Through their concepts humans appropriate to themselves isolated elements of reality, or single aspects of the things they know, without putting these aspects and isolated elements together as they are found in nature. Only through a series of judgments do they begin the process of unifying this knowledge to bring it into conformity with the constitution of things in the world. It is important to understand this, for truth about nature is acquired only gradually, with partial truths being grasped initially almost in piecemeal fashion. And when the intellect finally makes the unification in a way that corresponds to the actual unity found in the object known, the mind enunciates a proposition that is true and so attains truth. When the enunciation is at variance with the mode of being found in reality, the result is falsity. In apprehension, the senses and the intellect simply grasp an object as present to them and represent it as it is. Thus we can say that one either senses "green" and knows "grass" or one does not. Apprehension is a "go" and "no-go" operation that provides the materials on which a truthful judgment may be made without itself enunciating a truth. But in judgment, the dynamic act of combining and separating apprehended concepts, the mind no longer depends solely on the object represented but produces something new and original, a combination or separation contributed by itself. It is this original element, a new unity, that opens up the possibility of active or formal truth and falsity.

Active truth is also found in reasoning, the third act of the mind. Here the situation becomes more complicated, because two types of validity are found in reasoning, one relating to the matter or content of the propositions making up the argument, the other relating to the form of reasoning or the illation it employs. The first is truth in a proper sense as this is found in the judgment; the second is truth in an extended sense and is more properly referred to as correctness. An incorrect inference can, of course, lead to falsity in the conclusion, and thus the second type of validity is just as important for assuring the truth of a reasoning process as is the first. And both types are said to be active because, unlike the validity found in apprehensive knowledge, the intellect makes the connections that are involved, does this with its own judgment, and does so properly or not.

Given the intellect's natural propensity to attain knowledge, falsity, that is, the lack of conformity between the intellect and its object, is more difficult to explain than truth. The possibility of error or of falsity of judgment arises because judging is not a merely passive reception but an active synthesizing and interpreting of innumerable and diverse apprehensions at the level of both sense and intellect. When the intellect judges falsely it does so because it has not given sufficient attention or has not reflected adequately on the data of sense, the association of percepts, the reliability of memory, the connecting reasoning, or the validity of its principles. The intellect thus judges precipitately without reflecting fully on these sources and so not withholding its assent until sure it has sufficient evidence for it. In such a condition it asserts as true what only seems to be true, and hence it asserts beyond what it knows. It makes such an assertion under the influence of other powers, especially the will. The will, either because of its attachment to prejudices, or by its impatience or disinclination to effort, or by not applying attention, can move the intellect to judge what only seems to be. All falsity lies in this chasm between seeming and being. If something did not seem true, a person could not assent to it, since the intellect is a faculty of truth. Yet the intellect can take the seeming true for being true because its judgment is under the influence of the will, the emotions, and other powers. From the viewpoint of the intellect alone, no error is inevitable.

4.10 Computer Intelligence

This overview of knowing processes puts us in a position to contrast the vital operations of sensing, perceiving, and conceptualizing with the ways such operations may be simulated through the use of computers and similar artifacts. In so doing we again employ the three stages involved in a simple act of cognition (Secs. 4.2 and 4.4): first the physical stage, wherein an external stimulus originating in the object known impinges on a sense organ and produces a physical change in it; then the physiological stage, wherein the organ is itself modified or stimulated as a result of the physical change; and finally the psychic stage, wherein a mental representation or intentional form is produced as a result of the physiological change and the organism comes to know the object.

The simple sensation of sight as simulated by the photocell of the robot *machina speculatrix* (Sec. 3.6) achieves at best the first two stages of this process. The light source produces a physico-chemical change in the photocell and, as a result, generates a current that can be used for control purposes; the current may be seen as simulating a neural circuit and, if so, as modeling the physiological stage. There would seem to be no possibility that the robot possesses an intentional form in the sense in which this has been described in Secs. 4.8 and 4.9, and thus to say that it "sees" the light source would be to use "see" in an equivocal sense. The same could be said of the sensing of odors by the computer insect *Periplaneta computatrix* (Sec. 4.4). The chemical sensors in its antennae and mouth operate on physico-chemical changes that generate currents, and these again, at best, simulate the action of neural circuits in the robot's control system. But there is no possiblity of a mental representation of an odor in the neural circuits, and so the insect does not "smell" the odor in any meaningful sense of the term "smell."

The coordination of the various "sensing" activities in *Periplaneta computatrix* likewise falls short of the type of perceptual knowledge produced by the inner senses in an animal organism. The coordination in some way models the activities of the central sense in that it differentiates between the signals coming from the various types of sensors, but it does not integrate their outputs into a unified percept, and so it would be difficult to identify precisely what the computer insect "perceives." At best it detects bits and pieces of its environment, and through reacting to these in a programmed way, it succeeds in duplicating some of the activities of the cockroach.

More extensive claims have been made for what is called machine perception, and this likewise can help cast light on the complexity of perceptual processes. One area of study is pattern recognition, wherein an optical device is programmed to recognize simple patterns such as hand-printed letters.[16] Even though early devices of this kind were not able to segment continuous written material, they were said to "learn" to discriminate between various letter patterns when these were presented in random orientations. But obviously in such claims, "learn" is again being used in an equivocal sense. When a computer recognizes a pattern it compares what is seen by its kinescope with certain test features that serve to identify the pattern as one of a finite number of possibilities. The comparison it makes is not simply that of juxtaposition, as when two patterns are placed one on top of the other and viewed through a light source. Rather there is an indeterminacy in the standard pattern that is resolved on a probabilistic basis and corrected whenever the match is found wrong. By trial and error the computer advances toward its best identification of the pattern presented to it. But at no time does the computer sense the pattern, nor a fortiori does it perceive the pattern or anything else. It simply matches patterns against a variable standard until a satisfactory fit has been obtained.[17]

Similarly, computers are said to have a memory on the basis that they store information and make it available for future use. They do this by locating electronically bits of information that have been recorded and

16. Pioneering work on this problem at the Lincoln Laboratories associated with M.I.T. is described in O. G. Selfridge and Ulric Neisser, "Pattern Recognition," *Scientific American* 203 (1960), 60–68.

17. Much more advanced techniques for character recognition that employ parallel processing and neural networks to achieve better results are now being investigated; for details see Peter J. Denning, "Neural Networks," *American Scientist* 80.2 (1992), 426–429.

are present in the machine. Machine memory, on this description, is limited to recording the past as present, that is, it re-presents information in the present, much the way one locates a document that is physically present in a filing system. But animal memory as seen in humans is not limited to recalling matter received in the past as now present; rather, it perceives the past as past, that is, as temporally situated in a bygone present. A secretary who remembers filing a document does something different from another who merely locates the document in a file. The remembering focuses not on the present action, that of locating the material, but on identifying the past action, that of placing it in the file, precisely as a past action, i.e., as one done several days, weeks, or months ago. Thus a person may locate a document she or he has placed in a file and say, "I do not remember filing that." Clearly, recovering an item from a particular location is not the same as remembering when, how, and why it was put there.

Viewed in this way a computer may be said to "perceive" or to "remember" much the same as a camera may be said to "see," or a clock to "tell" time, or a tape recorder to "talk," or a videocorder to conserve a "memory" of the past. Each involves a simulation of one or another aspect of a cognitive process, without fulfilling the essential requirement of such a process, namely, that it be a vital operation wherein an object comes to be present in an immaterial or intentional way in a knowing subject.

More encouraging are the researches of neuroscientists who study how neural systems are activated in the brain when human subjects use language to communicate. Here there should be no doubt that the third stage of cognition has been achieved by the subjects being studied. Language, moreover, can be a vehicle for communicating not only sensations and percepts, the mental representations produced by the outer and inner senses respectively, but also concepts, the intentional forms that are unique to the human intellect. And since concepts are abstract and universal, as explained in Sec. 4.5, it might seem that in this way even human intelligence has come within reach of computer simulation.

But once again problems arise when one delves into the nature of cognition at its highest level, even through the delicate process of monitoring neural currents in the brains of intelligent subjects. The main difficulty is the close connection between perception and intellection as these occur in human beings. Not only is the percept necessary for the acquisition of concepts, as diagrammed in Fig. 4.2, but it seems that a person cannot entertain a concept or an idea without at the same time recalling and reverting to its associated percept or phantasm.[18] Thus, when a word or term is expressed, the brain activity accompanying the very expression is a sign of the percept, not a sign of the concept. The reason for this is that the word, like the percept, is singular and concrete; the concept, by definition, is abstract and universal, and even though it may be represented by a word, its universality, and the unique type of intentionality this involves, places it beyond the pale of material representation. More will be said about this in the following chapter (Sec. 5.8). Yet such a limitation in no way invalidates the research currently being done with PET (positron emission tomography) and other techniques to identify the brain systems involved in language activity.[19] With its help, even more than that provided by computer modeling, needed light is being cast on the key role played by the brain in human cognition.

With these considerations as a background, it is now possible to resume our discussion of animal natures left off at the end of Chap. 2. We turn therefore to the study of the special type of animal, the most perfect species within the animal kingdom, that of *homo sapiens,* which combines in its being cognitive powers of sense and intellect as well as appetitive powers of emotion and will. Such powers, and particularly those of intellect and will, open up for us the entire world of human endeavor. They are the ultimate sources of all the intellectual, moral, aesthetic, social, and political life to be found on planet Earth.

18. This was Aristotle's teaching in the *De anima,* Book III, chapter 7 (431a14–17), which was appropriated by Thomas Aquinas in his *Summa theologiae,* First Part, question 84, article 7.

19. This new technique is explained by Antonio and Hanna Damasio in "Brain and Language," *Scientific American* 267.3 (1992), 88–95; see also M. I. Posner and M. E. Raichle, *Images of Mind,* New York: W. H. Freeman, 1994.

5 Human Nature

Human life is very different from other forms of life found in the universe. In this chapter we shall address the questions of what it means to be a human being and what there is about *homo sapiens* that sets him apart from all other creatures. Why is it that when we juxtapose the terms "nature" and "human nature," we have the feeling that these terms refer to entities that have little in common? The answer is surely to be found in some eminent characteristic that differentiates the human from the nonhuman, or, to phrase this in language that is by now familiar, human nature from nonhuman natures. In identifying that characteristic it may prove helpful to retrace the path over which we have come in our exploration of natures of various kinds.

To this point the discussion of nature and natures has focused, first, on the definition of nature as the inner dimension of bodies composed of sensible matter (Chap. 1), and then on the broadest genera of natures found in the cosmos, namely, those of the inanimate or inorganic realm (Chap. 2) and those of the plant and animal kingdoms (Chap. 3). The natural or substancing forms (NF's) seen in this progression have revealed themselves as gaining more and more dominance over the inertness of protomatter (PM), manifested in the greater number of powers with which the natures are successively endowed. In plant natures one finds the basic life powers of self-movement (*sui-motio*), namely, the capacity of an organism to move itself from potentiality to activity. The vital activity thus initiated is self-perfecting in the sense that it is not action on another, passing outside the agent, as it were, but immanent, remaining within the agent. Such activity enables the plant to maintain its substantial unity and identity over a considerable period of time. Again, nourishing, growing, and maturing quite obviously perfect the individual organism that initiates these activities, and so does reproducing, even though the latter is perfective of the species as well as of the individual. Animal natures, in addition, possess powers of cognition and appetition that enable them to be aware of their environment and respond to it for their own benefit. The movements whereby they do so enable them to preserve self-identity and are even more distinctively self-perfective. Both of these characteristics, self-movement and immanence, assure that living things exist and operate at a higher level than do the nonliving. Organisms move themselves to fuller perfection and maturity through their interactions with other bodies, whereas inorganic bodies generally lose their energies and sometimes their existence when they interact with others.

As explained in the previous chapter (Secs. 4.5 and 4.7), the activity of cognition in some ways represents a greater break away from materiality than do other life activities. Knowing requires that the knower transcend its own limitations of space, and in some cases of time, to possess the form of another thing precisely as it is other. What is purely material in its being cannot engage in this type of activity. That is why intentionality in its very definition entails the notion of immateriality. An intentional presence cannot be other than an immaterial presence. But, as suggested by the various models of mind discussed in Chap. 4, different grades or degrees of immateriality are to be found in sense knowledge and intellectual knowledge respectively. The sensation and the percept differ from the concept, and the power that produces the latter, the intellect, is quite different in its mode of operation from the senses, both outer and inner. An animal nature such as that found in brutes has knowledge capabilities different from that found in humans. The burden of this chapter is delineating this difference in greater detail than heretofore by explaining all that is entailed in the expression "human nature"—not merely under the rubric of "mind," as previously, but considering the entire range of powers that are to be found in humans. Only when this is done can we appreciate fully what is truly eminent about human nature, and why we spontaneously recognize it as different from all other natures.

5.1 Life Powers and the Human Soul

In the classical definition, man is a rational animal, *animal rationale*, that is, an animal like other animals, but distinct by having the power of universal, abstract reason, and all that follows from it. Like all natural bodies, a human being is a union of protomatter (PM) and a natural form (NF), and like all living things, the natural form that informs and actualizes protomatter also animates or ensouls his or her body and so can properly be called a soul. To stress the fact that the human soul is such a natural form, essentially different from that of a plant or a brute animal, we shall henceforth designate it NF_h, with the subscript "h" standing for human. Human nature, the composite that results when NF_h is united to PM, while different from an inorganic nature, a plant nature, and an animal nature, nonetheless has elements in common with all three. Not surprisingly, it may be represented by a powers model that incorporates the major structures already treated in previous chapters. Such a model of human nature is shown in Fig. 5.1.

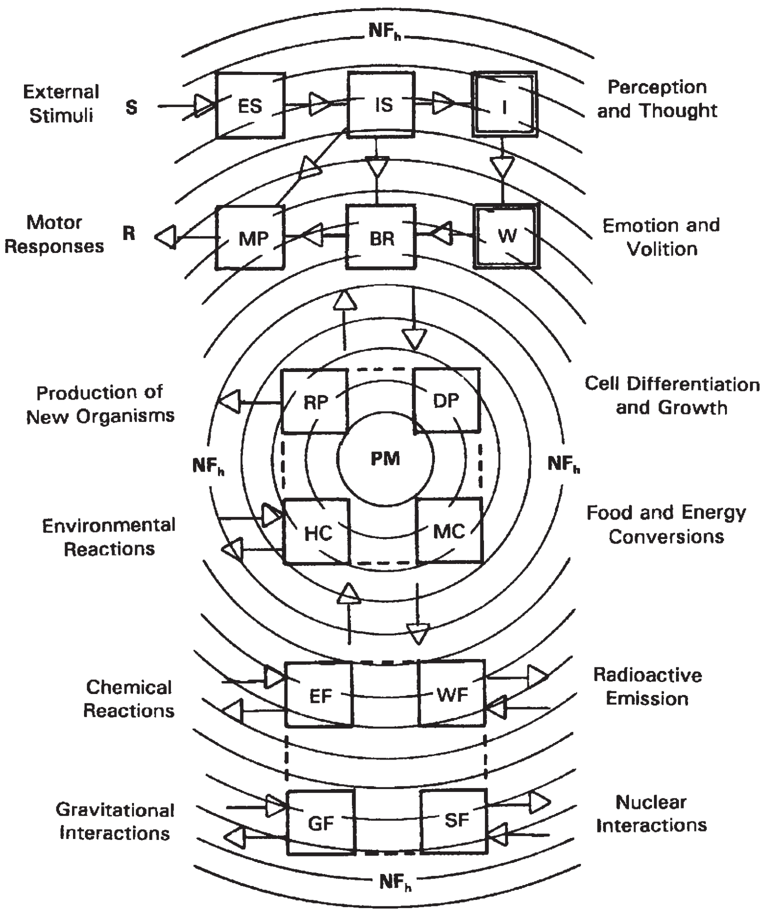

Fig. 5.1 A Powers Model of Human Nature

The major difference between human nature as presented here and the nature of a brute animal as modeled in Fig. 3.10 is lodged in the two boxes shown in double outline at the upper right and labeled with the letters I (for intellect) and W (for will). Intellect and will are the two highest powers in man, and in some ways they transform all the other powers humans have in common with plants and animals. They are unique to the human soul, which on their account is often referred to as an intellective or rational soul. It could also be called a volitional soul, for man is unique among animals in being able to initiate actions that are voluntary and for which he must assume responsibility. Intellect and will, as will be seen, work together as the root sources of activities that are distinctively human. Yet the ultimate explanation of these activities is found in the fact that man is a reasoning or discursive animal, as expressed in the classical definition.

The human body is an essential part of man, and yet the relationship between it and the human soul is such that the body exists, not in its own right, but in virtue of its protomatter having been informed by the rational soul. As explained earlier in Secs. 1.2 and 1.3, the natural form is a determining and specifying form, or, in other words, a substancing form. When activating the potentiality of protomatter it produces a substance that is essentially one, a substantial unity, though constituted from two co-principles, matter (*hulē*) and form (*morphē*). From the Greek terms this ontic unity, already touched on in Secs. 3.7 and 4.1, is referred to as "hylomorphic." The sense is that man is more than a mere juxtaposition of parts that exist in independence of each other. Rather the human being is a whole constituted from co-principles that go to form an essential unity. And though both factors contribute to the being of the whole, the human form or rational soul is the more principal of the two. The human body is human only through the soul, for it is the soul that determines the body to be human and not vice versa.[1] On this accounting, the hylomorphic relationship can serve to explain the psychosomatic unity (i.e., that of *psuchē-sōma*) of the human being.

The essential unity of man is manifest from the fact that the same concrete being who experiences a bodily presence also recognizes this

1. We bypass here the problem of hominization, that is, how and when the human soul comes to be present in the body. For a discussion of this problem in terms of the powers models developed in previous chapters of this study, see our "Nature, Human Nature, and Norms for Medical Ethics," *Catholic Perspectives on Medical Morals: Foundational Issues*, ed. E. D. Pellegrino et al., Dordrecht-Boston-London: Kluwer Academic Publishers, 1989, 23–53. A fuller treatment is that of Norman N. Ford, *When Did I Begin? Conception of the Human Individual in History, Philosophy and Science*. Cambridge: Cambridge University Press, 1989.

presence as that of a person who thinks.[2] The mental activity of thinking and the material givenness of the body are both manifestations of one and the same human reality. Again, intellection as a cognitive process manifests a higher degree of immateriality than do sensation and perception, so that one may say that in thinking the soul is essentially independent of matter (see Sec. 5.8). On the other hand, a human being is really material, and this not merely accidentally, for the body belongs essentially to human nature. Now, the only way in which one can reconcile these apparently conflicting data is to maintain that the human soul informs matter as a natural form. Such a special and intimate ontological relationship between soul and body alone explains man's substantial unity, the immateriality of the human soul, and the fact that a body is an essential part of human nature.

The human soul, on this understanding, may be modeled as the energizing field NF_h shown in Fig. 5.1 as radiating out from protomatter and duplicating in most matters the psychosomatic functions earlier attributed to plant souls and animal souls in Sec. 3.7. This energizing field is the primary actualizer of protomatter in the case of humans as well as of plants and animals. As in their case, the energies of the natural form (here the human soul), require further specification and actualization through its powers, which again are shown as boxes distributed throughout the field. The four physico-chemical powers at the bottom of the field are not localized at the macro-level, being found throughout the human body in the molecules and macro-molecules that enter into its constitution as integral parts. Neither are all of the plant powers, for although some, such as the reproductive and nutritive powers, exert their influence mainly in the organs that serve these functions in the human body, others, such as the homeostatic and the developmental powers, have effects throughout the entire body. It is at the level of the animal functions, of course, that the greatest changes take place, for although still an animal, man is an animal of a very special type, one with cognitive and appetitive powers superior to those found in other animals. These are shown in the boxes, now six in number as contrasted with the four in Fig. 3.10, spread across the top of the diagram—supported, as it were, by the vegetative and inorganic powers below.

2. Thomas Aquinas, when arguing against the Averroists of his day, saw this as conclusive evidence that the human soul is the substancing or natural form of the body: "If anyone does not wish to say that the intellectual soul is the form of the body, let him find a theory whereby the act of understanding is the action of this man, for everyone knows by experience that *he* understands"—*Summa theologiae*, First Part, question 76, article 1.

As in the case of other animals, the higher powers are again represented as a stimulus-response system. When energized by appropriate stimuli (S) at the top left, the three sets of cognitive powers are activated more or less sequentially: first the external senses (ES), then the internal senses (IS), and finally the intellect (I), shown in double outline. The latter two of these are then able to activate their corresponding appetitive powers, the internal senses having the capability to elicit a behavioral response (BR) and the intellect, to move the will (W), likewise shown in double outline. These in turn act on the motor powers (MP) to produce a response (R) to the stimuli. It is also possible for the internal senses, acting directly through the nervous system, to produce an autonomic response, as shown by the diagonal arrow running from IS to MP.[3]

All of the major differences between man and brute animals are traceable to influences exerted by intellect and will on man's other powers. Human skin and the organs situated in the external envelope of the body differ in obvious ways from those of the lower animals, mainly because they are supplemented by more refined internal senses and by a reasoning ability that lower animals lack. Man's emotional responses are more varied and more controlled than those of brutes, largely because of the influence of mind and will over human action. And because human beings can understand their vegetative powers and the organ systems through which these function, as well as the biochemistry that operates through their inorganic powers, they can preserve health and vitality in many ways not available to other animals. To do all this, however, their intellects and wills have to be perfected by habits and virtues with which they are not endowed from birth. Man is not only a rational animal but also a perfectible animal, perfectible in ways to be discussed in subsequent sections of this chapter.

To sum up, the human soul is a natural or substantial form, like other such forms found in the universe, yet different in the powers it possesses. These powers are innate to man, and still the higher powers operate more easily and more efficiently when they are perfected by habits that become a sort of "second nature" to their possessor. Science, for example, is a typical habit of the intellect, making the person who possesses it a scientist of one type or another. Similarly, justice is a typical habit of the will, making the person who possesses it just, that is, inclined to render to others their due. Neither of these habits is innate; both have to be ac-

3. The entire system has already been diagrammed in the preceding chapter (Fig. 4.3, Sec. 4.5), where it was introduced as a model to explain intentionality as this is found in intellection as well as in volition.

quired through exercise and repeated actions. And finally, though this is not clearly indicated on Fig. 5.1, as shown on Figs. 4.2 and 4.3 the intellect is dependent on the inner senses, and particularly on the percept, for the formation of concepts, the basic units of the intellectual life. As already indicated in Sec. 4.5, the intellect depends on the body and its senses, both external and internal, for its source materials, and thus it is in some way dependent on matter for its immaterial thought processes.

Human nature, of course, is modeled by the energizing field laid over all these powers as illustrated in Fig. 5.1. Like previous models of natures, this is not a model of an individual person. Rather, it applies to the species as a whole and so should be thought of as instantiated in each and every adult human organism. Human nature, and the human soul in particular, is thus the unifying and stabilizing principle to which all of man's life activities can be traced—the primary principle, in Aristotle's words, "by which we live or sense or think."[4] In virtue of that principle a person not only senses and thinks but also wills, perceives, reacts emotionally, and moves the limbs. It lies behind the homeostatic equilibrium humans maintain with their environment, the metabolism whereby they assimilate their food, the processes through which their bodies grow and develop and ultimately reproduce. It even explains the ways in which ion concentrations are maintained in the body fluids, how radioactive tracers are carried to one or another of the organs, and ultimately why the body floats in water and falls in accordance with the laws of gravity. In a word, this natural form is what makes a person one organism, with a diversity of parts, each capable of being coordinated in unified activity, which reaches its perfection in the use of reason and the exercise of free will.

5.2 Entitative Perfection

With this ensemble of powers and capabilities before us, it is appropriate here to address the problem of the entitative perfection of natures, that is, their perfection in being (*ens*), for the light it may shed on their operational perfection, their perfection in works (*opera*), a topic that will require treatment below.[5] As already suggested, there seem to be de-

4. *De anima*, Book 2, chap. 2, 414a13–14.

5. These Latin terms, *ens* and *opera*, give rise to the adjectives *entitativa* and *operativa*, which are used in the Aristotelian tradition to characterize these two types of perfections or habits, the entitative and the operative, the first treated in this section, the second in Sec. 5.7.

grees of perfection in natures according as they manifest more and better powers or capabilities. In this sense, plants are superior to minerals, animals to plants, and humans to animals. Even within a kingdom or species, or within an individual over time, however, it is possible to speak of one state being better than another. This is difficult to see in the inorganic realm, though perhaps one could say that a diamond is better than a piece of charcoal though the chemical nature is the same in both—pure carbon. Crystals and precious gems seem to manifest the perfection of an inorganic nature by showing it in its most stable and unified state, thus best able to conserve its being against deleterious environmental influences.

In the realm of the living, some individuals are better adapted than others, stronger and more agile, for example, and so, as Darwin pointed out, more fit for survival. But individuals themselves vary over time in their capacity for exercising life functions from time to time. At one period their organ systems might be working well, at another not. There is a general name for this well-working of an organism as a whole, and that is "health." Plants and animals are said to be healthy when their natural powers activate their organs properly and all their systems are functioning. Then they are said to be "well" themselves—our common way of indicating that we are healthy. There is such a thing as a healthy geranium and a healthy squirrel, and, of course, our preeminent concern is with the healthy human being. This is the sense of entitative perfection that first requires attention.

What is health, and how does it relate to a nature that is said to be healthy? As a preliminary definition we may propose that health is a habit or disposition that characterizes the organism as a whole, but that is especially manifest in the way a natural power energizes or activates its respective organ system. In this sense one can have a healthy liver, healthy circulation, and healthy limbs; the aggregate of all these healthy systems constitutes the health of the organism. This state is modeled in Fig. 5.2, showing, as heretofore, the natural powers of an animal. Now, however, small hexagons have been added to the squares or boxes of earlier diagrams. Up to this point squares have represented powers, or, in the case of the inorganic, forces or potentials. The new hexagons stand for habits, or dispositions, or traits that characterize the ways in which these powers operate. Inorganic powers do not acquire dispositions in the commonly accepted sense, and so have not been shown in this figure. But hexagons have been added to all the vegetative and animal powers, for these can be said to be properly disposed or healthy in the way they function. The arrows again represent lines of causal influence. In some instances hexagons have been added to the lines to suggest, over and above the power's functioning, a healthy influence on a power to which it is related.

By way of illustration, Fig. 5.2 may be seen as modeling the life powers of a healthy squirrel. The hexagon on the external senses box (ES) then indicates that the organs for these senses are healthy and functioning properly, that the squirrel sees and hears as a squirrel should, and that under proper stimulus (S) these sensations are transmitted without defect to the internal senses box (IS). If the brain and nervous system are healthy, percepts are formed there and correctly activate the motor powers (MP), provoking the autonomic reaction indicated by the diagonal line from IS to MP. Then, if the nervous system, muscles, and limbs are healthy, the squirrel reacts in sprightly fashion to the signal that has been received, here indicated by the response arrow (R) with its accompanying hexagon. Alternatively, the estimative or instinctive sense, if correctly evaluating the percepts received, may provoke a behavioral response (BR) within the brain and nervous system that initiates affective or aggressive action along the horizontal line running from BR to MP.

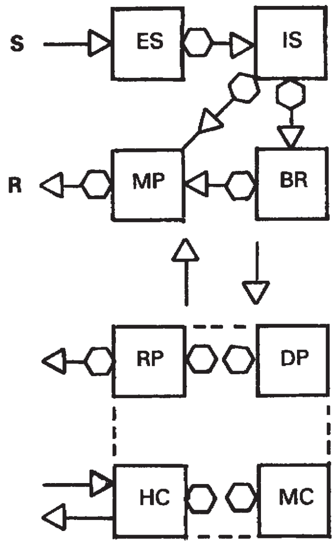

Fig. 5.2 Powers of a Healthy Animal

Similar functioning will serve to describe the healthy operation of the squirrel's vegetative powers. If the internal organs are in good order, its homeostasis (HC) and metabolism (MC) will maintain it in proper relationship to its environment and it will be assimilating food to supply the energy required for vital operations. Its developmental powers (DP) will assure proper growth and cell replacement, and its reproductive system (RP) at the adult stage will be producing healthy egg and sperm cells from which one or more baby squirrels, themselves healthy, will ultimately be produced. In all, therefore, one would say that the squirrel is a healthy animal, having all that it as an individual of the species requires for its life functions. And its health is relative to the particular organism as a whole, being more qualitative than quantitative in its basic conception. One squirrel's health is not another's, for there are individual differences among organisms that militate against there being universal quantitative standards for the entire species.[6]

It is a simple matter to upgrade Fig. 5.2 and diagram the vegetative and animal powers of a healthy human being along analogous lines. A problem presents itself, however, with the intellect and the will, for these powers do not depend on organ systems for their operation and so are not perfected in the same way.[7] The problem can be circumvented by extending the sense of entitative perfection to include more than bodily health. There is also a type of health that is peculiarly human, namely, the health of the mind. The mind is healthy when it thinks properly, and this requires more than a sound body, more than a healthy brain and nervous system. It requires also that the intellect be habituated to correct ways of thinking about various subject matters. Such habits are generally called intellectual virtues—"intellectual" because they perfect the intellect, "virtues" because they strengthen it in its various mental operations. These virtues are commonly classified into two types: some are called sciences, others, arts. Science in this understanding has a broad connotation, that of being able to think surely and systematically about a particular subject matter. Thus it may be regarded as an entitative perfection of the mind, much in the way that health may be regarded as a similar perfection of the body. Art is similar to science, excepting that it has an additional connotation: apart from being concerned with "think-

6. Leon Kass's description of a healthy squirrel characterizes this situation very well: ". . . it is ultimately to the workings of the whole animal that we must turn to discover its healthiness. What, for example, is a healthy squirrel? Not a picture of a squirrel, not really or fully the sleeping squirrel, not even the aggregate of his normal blood pressure, serum calcium, total body zinc, normal digestion, fertility, and the like. Rather, the healthy squirrel is a bushy-tailed fellow who looks and acts like a squirrel; who leaps through the trees with great daring; who gathers, buries, and covers but later uncovers and recovers his acorns; who perches out on a limb cracking his nuts, sniffing the air for smells of danger, alert, cautious, with his tail beating rhythmically; who chatters and plays and courts and mates, and rears his young in large improbable looking homes at the tops of trees; who fights with vigor and forages with cunning; who shows spiritedness, even anger, and more prudence than many human beings"—"Regarding the End of Medicine and the Pursuit of Health," *The Great Ideas Today 1978*, Chicago: Encyclopaedia Britannica, 1978, 90.

7. As already explained, the intellect depends on the inner senses for the percepts from which it extracts intelligible meaning, and thus it depends on sensory organ systems for its acquisition of knowledge. It does not depend on the percept, however, for its operation, that is, for its processing of knowledge, all of which takes place within the intellect itself. This dependence is sometimes referred to as an "objective" dependence, since the intellect is dependent on organs for the object of its knowledge.

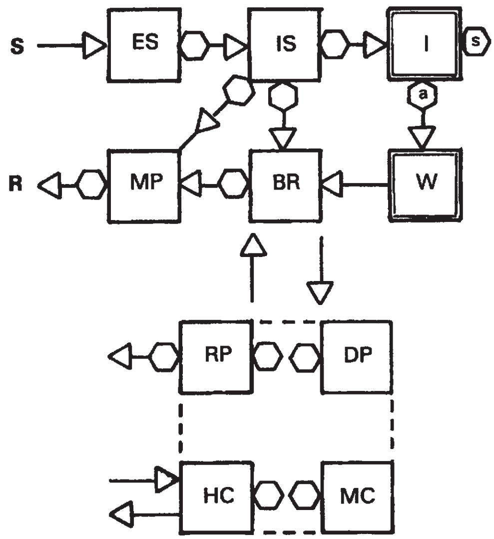

Fig. 5.3 Powers of a Healthy Human Organism

ing," like science, it is also concerned with "doing" or "making." Grammar, for example, is an art that enables humans to speak and write correctly. To do so they must know the rules of syntax that govern their native language, and then they must apply them in speech or in writing. Talking is different from thinking, and so is writing, for both require an effort of the will and additional powers beyond that of the intellect.

Figure 5.3, on this basis, attempts to model the natural powers of the healthy human organism. Only the powers in the central and upper portions of Fig. 5.1 are here reproduced, since the inorganic powers are again not pertinent to this consideration. Bodily health is represented in the same way as in Fig. 5.2. Mental health, in addition, is shown by the proper functioning of the inner senses (IS)—perception, imagination, memory, estimation—which now take on a twofold relationship. The first is to behavioral response (BR), seat of the emotions and the primary locus for mental illness in humans, and the second is to the intellect, where the percepts they provide become the basis for concept formation along the lines already indicated in Sec. 4.5. The intellect itself (I) is indicated as perfected in the cognitive line by science, the habit of thinking correctly and consistently arriving at truth in different areas of investigation. This is shown as a hexagon with the letter "s," to distinguish it from the symbol for bodily health. Similarly, the intellect is portrayed as also directed downward toward the will (W), the first source of human action, in which direction it is perfected by one or more of the arts. This is indicated by a hexagon with the letter "a," again to differentiate it from the symbol for bodily health. The healthy human being is thus one possessed of all the entitative perfections that have been discussed in this section: those that perfect the organ systems of plant and animal life, as well as those that perfect the mind so that it functions in proper human fashion.

5.3 Human Cognition

Turning then to a fuller explanation of human knowing, we first concentrate on the inner senses and the special ways in which they function in the human being as contrasted with the lower animals. In the case of the latter, as diagrammed in Fig. 5.2, perception in the inner senses (IS) is the culmination of cognitive activity, and thus what it perceives either influences the motive powers (MP) directly in an autonomic reaction or else provokes an emotional response by way of the sense appetites (BR). In the case of humans, as diagrammed in Fig. 5.3, the inner senses look not only to the motor powers and the emotions, but also to the intellect (I). The basic reason for this, as explained more fully in Sec. 4.5, is that the inner senses provide the percepts from which the active or creative intellect extracts the meaning or intelligible content that then is expressed in the concept. This additional function suggests that the inner senses operate somewhat differently in man than they do in brute animals. They do so mainly in two sense powers, the estimative sense and the memory.

Inner Senses. So different is the functioning of the estimative or instinctive sense in man that it is given a new name, the cogitative power (*vis cogitativa*) or the discursive power. In Sec. 4.5 reference was made to the close working together of perception and intellection, a functioning that itself suggests cogitation. Another name used to characterize the operation of this sense is "particular reason" (*ratio particularis*), for an incipient type of discourse takes place in it that may be likened to a collation of singulars or particulars. By assembling percepts in a quasi-intelligent way, the cogitative power prepares material for the intellect, as it were, and thus renders somewhat easier the formation of the universal in the concept. In the early stages of human life, for example, in infants, the cogitative sense would seem to stand in for the intellect while the latter is still in the process of forming its concepts.

As already discussed in Sec. 4.3, the estimative sense in lower animals attaches a value to the percept as being good or bad, that is, as beneficial or harmful to the organism, and so elicits an appropriate emotional response. Likewise in humans the cogitative power recognizes good and bad in concrete particulars. This is not to say that it grasps goodness and the relationship this concept has to an appetitive power, for only the intellect is capable of grasping universals of this type. And yet human beings seem to learn concrete good and bad by a kind of comparison of individual instances. The slow and uncertain way in which an individual learns, and even the relativity of human opinions about good and evil discovered in anthropological research, lend support to such a role for the cogitative sense.

Memory in humans also is a more refined sense than in brute animals. This again comes about because of the close relationship the inner senses in human beings have to the intellect. As previously explained, animal memory stores up particulars to form a repository of past experience on which the organism can draw for the future. Human memory adds to this a superior mode of operating that may be called recollection (Lat. *reminiscentia*), that is, the ability to search for and recall items that may have slipped from memory and so seem forgotten. Indeed, by focusing on even a portion of a previous experience, the intellect can frequently reconstruct it in its entirety and so recover completely incidents from the past. Animals, on the other hand, seem restricted to instant recall, recognizing something from the past either spontaneously or not at all.

Self-Awareness. The activity of recalling, though exercised in this case through reflection on percepts provided by the internal senses, brings out another point about human cognition that should be stressed. This is the higher degree of immateriality already referred to, which enables the human knower to reflect back on his or her own knowing act and thus achieve a level of knowledge that is impossible for both the outer and inner senses when operating alone. An example of this has already been seen in Secs. 4.6 and 4.7 in the discussion of logical concepts and the first and second intentionalities these entail. Humans can examine the contents of their minds, as it were, and use these contents to develop disciplines such as logic and psychology. Not only can they know sensitively and intellectually, but they can know *that* they know, simply by reflecting on their own knowledge experiences. This is but a variation on the process called introspection—a technique rejected out of hand by early behaviorists of the "black box" period, but since restored to favor with the rise of cognitive science. Through its use individuals have a privileged view or insight into human nature, the nature that thus becomes most knowable to them. And since human nature contains within itself all the powers discussed to this point, it also gives them an insight into the other natures that make up the cosmos.

On this accounting, humans are aware not only of their cognitive activities but also of their appetitive powers, their motor powers, and their vegetative powers as well. Adults surely are conscious of their ability to reproduce, and although growth and development take time and are not instantly perceived, even by the young, all are aware of the capabilities of their digestive and eliminative systems to convert food to usable energy and dispose of waste products. One person pushing against another provides both with a direct knowledge of force and how it can produce motion. Similarly, experience with thrown or moving objects gives some idea of momentum and kinetic energy, and changes in the speed or direction of motion, as sensed in an elevator or an airplane, quickly familiarizes a person with g, the acceleration due to gravity.

These few illustrations bring out an important point about human nature, namely, that it includes within itself, and so makes almost transparent to the intellect, all the virtualities or powers found in animal, plant, and inorganic natures. To say this is not to anthropomorphize nature, as some might suspect, but simply to acknowledge that man is a material being, a body among other bodies, each of which shares some element found in human nature, though in a somewhat different way. This can be summed up in the oft-acknowledged fact that man is a microcosm. In knowing oneself, one gains a privileged insight into the natures that make up this minicosmos, with the result that they become more intelligible in themselves. Moreover, anyone ranging over all the human sciences will see how much they incorporate within their own fabric the essentials of physics, chemistry, biology, and psychology, and so require knowledge of these subjects for their own understanding.

Reflecting in this way on the various disciplines with which the human mind can be occupied enables us to focus on the sciences and the arts that have developed over the centuries and to investigate more fully the ways in which they can be said to perfect the human intellect. In view of the concentration in the second part of this volume on recent science, attention will be directed here to the more classical understanding of science and to the way it is related to the other intellectual virtue in which we are here interested, namely, art and its various types—liberal, fine, mechanical, and so on.

Sciences. In its premodern understanding, the term science (Lat. *scientia*) designates a type of perfect knowing (*scire simpliciter*). For Aristotle, one obtains such knowledge of any object when one knows (1) its cause, (2) that that cause makes the object be what it is, and therefore (3) that the object could not be otherwise than it is.[8] For St. Thomas Aquinas, science is knowledge of something through its proper causes.[9] It is located in the category of intellectual knowledge, as opposed to sense knowledge; and within this category it is characterized as mediate intellectual knowledge, as opposed to the immediate knowledge of concepts and first principles, insofar as it is acquired through the prior knowledge of principles and causes. For both Aristotle and Aquinas, scientific knowing in the perfect sense is true and certain and thus not open to radical revision, though it can grow on the basis of new experiences and be refined by way of reclassification and changes in terminology this may entail. Apart from this strict notion, both these philosophers allowed application of the term to less perfect types of knowing, including those based on tentative explanations and those that merely "save the appearances," somewhat akin to the explanations of modern science.

Sciences can be classified in various ways. One of the most basic divisions is that into speculative science, which is concerned primarily with knowing and not with doing, and practical science, which is concerned with knowing as ordered to doing. Speculative sciences are then further differentiated on the basis of the ways they attain knowledge of the objects they treat. All of them have their origin in sense knowledge, and so all commence with the same material objects. They differ in the ways they abstract intelligible content from those objects, as indicated in the previous chapter (Sec. 4.6). Thus the broad genera of speculative sciences are natural science, mathematics, and metaphysics, each more abstract in its consideration. Further specification is then introduced on the basis of different subjects of study and the principles appropriate for their investigation. For example, natural science may be divided into the physical sciences, the life sciences, and the human sciences. Then, the physical sciences may be classified into physics, chemistry, geology, etc., the life sciences into biology, botany, zoology, etc., and the human sciences into anthropology, psychology, sociology, etc.

In the resulting division of the sciences, it may turn out that the principles proper to one subject of investigation can be applied fruitfully to another subject, and then it is possible to generate a hybrid or mixed or intermediate science (Lat. *scientia mixta, scientia media*). A recent example would be biochemistry, which uses the principles of chemistry to

8. *Posterior Analytics*, Book I, chapter 2, 71b8–12.
9. *Summa contra gentiles*, Book 1, chapter 94.

investigate various life processes. A much older example is mathematical physics, a science intermediate between mathematics and natural science, which takes the same subject for its consideration as does natural science but considers it under the light of mathematical principles. This type of *scientia media* was known to Aristotle, practiced by Archimedes and Ptolemy, and perfected gradually over the centuries, until it culminated in the classics on which modern science is based, viz., Galileo's *Two New Sciences* (1638) and Newton's *Mathematical Principles of Natural Philosophy* (1687).

Practical sciences, like speculative sciences, seek knowledge through causes, for this is what enables them to achieve the perfect type of knowing described above. Examples of practical sciences are moral science, which is concerned with human action, medical science, which is concerned with health, and engineering science, which is concerned with producing mechanical, structural, and other artifacts. What differentiates each of these from a speculative science is that the latter seeks causal knowledge of what a person can only know, that is, universals, whereas a practical science seeks causal knowledge of what a person can do or make, namely, singular operables. To the extent that a practical science engages in causal analysis, it can speculate and use analytical procedures similar to those of the speculative sciences. But whereas a speculative science seeks only to know its subject in an apodictic way, a practical science aims to make or produce a concrete instantiation of that subject and must be supplemented by an art or technique that deals with singulars in order to do so. How this works will be exemplified in some detail below in Secs. 5.6 and 5.7.

Arts. None of the practical sciences is concerned with truth or certitude for its own sake. They do attain a type of practical truth and practical certitude, however, and this is determined by their conformity or adherence to the norms or rules that determine sound practice. It is difficult to draw a sharp line of demarcation between any practical science and the art or arts associated with it, because both practical science and art are judged by their conformity to rules. It can be said, however, that art is more properly concerned with the actual construction of the singular object or operable and that its truth is thus judged by freedom from errors in execution. A practical science is more properly concerned with causal analysis that will lead to proper construction of the object or operable and is thus judged true on the basis of its ability to provide sound norms for such execution.

Apart from such arts associated with practical sciences, there are other arts with different applications. In its classical meaning an art is essentially a good judgment about making something (Lat. *recta ratio factibilium*, the correct formula for things to be made), where the "made" means that the product results from physical work. This meaning applies only to the servile or mechanical arts and not to the liberal or fine arts. Liberal arts make nothing physical but are concerned only with works of the mind such as the arrangement of ideas. They are called liberal because in ancient times they were proper to free men, in contradistinction to the servile, which then were proper to slaves. Clearly they pertain to man's contemplative or speculative life rather than to his active or productive life. Among the liberal arts the most important are logic, whose subject matter has been discussed in the preceding chapter, and grammar, which is concerned with the external expression of thought. Logic is further subdivided into demonstrative logic, which aims at science and certitude; dialectical logic, which analyzes less rigorous types of reasoning and aims at probability or opinion; and rhetorical logic, which is similar to dialectics but aims at persuasion. All of them serve as instruments for the sciences, albeit in different ways.

The fine arts have elements in common with the liberal arts, though they are concerned with external expression and use nonverbal symbols. For Aquinas, those that are purely compositive, say, the composing of literature or music, he regarded as liberal arts in the strict sense. Those that involve the external execution of a work, say, acting, playing a musical instrument, or sculpting, he considered servile disciplines even though the works they produce are liberal in function.

All of these arts and sciences are, in effect, habits or virtues of the intellect, though again they perfect it in different ways. As illustrated in Fig. 5.3, the sciences (symbolized by the hexagon marked with an "s") enable the one possessing them to think in disciplined fashion. Their possession then serves to denominate the person equipped with them a scientist (physicist, biologist, etc.), a mathematician, or a metaphysician. Physicians and engineers are also scientists in that their minds are perfected in similar ways, but to engage in "doctoring" or "engineering" they require associated arts in addition. These are symbolized by the hexagon marked with an "a" in Fig. 5.3. In less technical contexts the same letter designates the liberal and fine arts as well. The arts and the sciences thus bring human knowing to a state of entitative perfection never found in the subhuman, even though lower animals sometimes surpass humans in the acuteness and sensitivity of their powers of sense.

5.4 Appetition and Emotion

Apart from cognitive powers, organisms that possess knowledge also have powers that incline them to seek or avoid the objects with which their knowing powers put them in contact. As introduced above in Sec. 4.3 such powers are called appetites, and they are stimulated or aroused by cognitive acts. The evidence for the existence of appetites is, first, one's own experience, and, second, one's observation of other animals. A person feels impulses and affects aroused interiorly by cognitive acts toward various objects, and these usually stimulate his or her action toward such objects. Moreover, animals seem to act the same way and have the same kind of organs as humans. Thus knowing beings give evidence of having the capacity to be moved by objects as known, and this capacity is, by definition, an appetite.

Appetites. Since appetites are the natural counterparts of cognitive acts, there are as many kinds of appetite as there are different kinds of knowledge. Cognition or knowledge, as explained in the previous chapter, is divided into sense knowlege (sensation and perception) and intellectual or rational knowledge (intellection). Similarly, appetition or appetite is divided into sensitive appetite and rational appetite. Rational appetite is commonly called will, and treatment of it and its exercise, also known as volition, will be postponed until the following section.

A sensitive appetite may be defined as a capacity to be aroused by a concrete object perceived through the senses. It is therefore an operative power, that is, a power to respond and react. This response or reaction on the part of the organism possessing the appetite usually occurs in two stages. The first is a kind of passivity by which the power is changed or moved by the impact of the object sensed. The second follows when the change produces a tension in the organism, which inclines it to action for the purpose of relieving the tension. On this account appetites tend to provoke action. The actions are designed to obtain or avoid the object that originally aroused the appetite: to obtain it if it is good, to avoid it if it is evil. Since avoiding evil is itself a good, one may define the appetite as ordered simply to the good, and this either directly or indirectly, the latter by avoiding its opposed evil.

Emotions. Sense appetites also involve physiological changes in the organism, and these result in distinctive types of actions. The physiological changes may be greater or less, but they are always present and are recognized as the emotional components of changes in the brain and in the nervous, circulatory, respiratory, glandular, etc., systems. The types of actions that result are known as emotions. An emotion may be defined as the felt tendency toward anything intuitively appraised as good or beneficial, or away from anything intuitively appraised as bad or harmful, with the attraction or aversion being accompanied by a pattern of physiological changes organized toward appropriate action.

Emotions are classified into two general types, as are the appetites that elicit them, on the basis of the following reasoning. Some emotions in the organism are aroused on the basis of simple pleasure or pain, as it seeks out what is pleasing physically and avoids what feels injurious. These reactions constitute the operations of one sensitive appetite, called the impulse or affective appetite, whose ultimate object is defined as the readily attainable sensitive good. Other emotional reactions are not so simply explained, for example, inclinations impelling one toward things that are hard to obtain, or emotional responses impelling the knower to reject difficult goods or despair of their attainment. Such appetitive reactions are therefore assigned to a second sensitive appetite, called the contending or aggressive appetite, whose object is the difficult or arduous sensible good.

Further classifications may be made on the basis of the different conditions under which a given object can affect a person. These can be classified in the following way: the thing is either good or bad for the person; it is either present or absent; and it is easy or difficult to attain or avoid. When these conditions are applied to the impulse emotions, it turns out that six basic emotions may be categorized, three of which are directed toward the good or beneficial, namely, love, desire, and joy, and three toward the bad or harmful, namely, hate, aversion, and sadness. *Love* may be defined as the simple tendency toward a good thing, and it is the fundamental reaction that underlies all others. *Desire* arises from love, for it is a tendency toward a good that is not yet possessed but is presently attainable. *Joy* follows directly from desire when the good is actually possessed. If the object is an evil, the opposite emotions result. *Hate*, the reverse of love, is the turning away from an evil thing. *Aversion* or dislike arises from hate, as an actual repugnance to an evil that first presents itself. *Sadness* or sorrow follows after aversion, if the evil is actually upon one and cannot be escaped.

When these conditions are applied to the contending emotions, on the other hand, only five of these may be distinguished. Two of these are toward the good or beneficial, namely, longing and despair, and three toward the bad or harmful, namely, courage, fear, and anger. *Longing*, like love, is a tendency toward the good, but it differs from love in that it is a vehement seeking for a good that is hard to obtain. *Despair* is the reverse of longing: it is the giving up of a good because it is judged too difficult to gain. *Courage* results when individuals estimate the evil as something they can cope with and so attack it energetically. *Fear* arises when they appraise it as too difficult to contend with and have the urge to avoid it or flee from it. *Anger* emerges when what is disliked is actually upon them, when it frustrates and obstructs them even though they feel it can be overcome and still have the urge to attack it.

These eleven are listed as the basic emotions; all may vary in degree of intensity and may be given different names on that account. With the impulse emotions, love may become delight or ecstasy, desire may become passion, hate may become abhorrence or loathing. With the contending, when the striving for something one likes becomes intense, it becomes a craving. Similarly, anger may become desperation and fear may become terror.

From the above, it may be seen that emotions are passions of the soul that are elicited by sense knowledge and that have concomitant effects in the body. Like purely physiological appetites such as hunger or thirst, emotions are action tendencies. But emotions are not themselves activated by a physiological state, nor do they aim toward a naturally determined object. Anger, fear, love, or hate is felt whenever a sensed situation is appraised as annoying, threatening, good, or bad. Though there is a physiological state specific for each emotion, this state is induced after the sensible object is seen and appraised. In fear, for example, this estimate activates the sympathetic nervous system, the adrenal gland begins to secrete adrenalin, and various physical changes become noticeable. But the racing heart, trembling knees, and dry mouth come *after* the estimate, not before. In contrast, physiological appetites are activated by a physiological state that has its own instinctive rhythm. Hunger recurs even when nothing edible is in sight. Instead of being stimulated by the internal senses, the reverse actually occurs: hunger activates the imagination, with the result that the animal organism begins to look for food.

5.5 Volition

We come now to the second kind of appetite in humans, the intellectual or rational appetite, known as the will, the conative counterpart of the intellect, shown under the intellect in double outline in Figs. 5.1 and 5.3. The will is the source of a special type of appetition called volition, namely, a seeking after the special type of good that is perceived by the intellect alone and not by the senses. Just as the intellect is the supreme cognitive power in human nature, so the will is the supreme appetitive power, and it controls all distinctively human behavior. By its natural inclination the will is not directed primarily toward concrete and sensible goods; it is concerned instead with intelligible or rational goods as these are presented to it by the intellect. It seeks such rational goods and rejects their opposites, rational evils. Thus the will tends toward or desires justice, truth, order, and immortality, and it turns away from or dislikes injustice, deceit, disorder, and death.

The will is not limited in its consideration, however, to abstract and intelligible goods but seeks also to obtain or avoid objects that appeal directly to the sensitive appetites. When it acts in this sphere, it does so because it sees reasonableness (or its opposite) in such objects. Thus, the sight of food might arouse the impulse appetites because food is pleasant to eat, but a person wills to eat it only if it is reasonable here and now to do so. Humans can also starve themselves in spite of contrary urging from the sense appetites, if in the circumstances they judge this a reasonable thing to do. The will is therefore the ultimate control on all behavior that is properly human, as long as the person is conscious and sane. Even behavior that is motivated primarily by the sense appetites is not carried out unless the will consents.

The will is the source of a person's voluntary activity—called such from the Lat. *voluntas*, meaning will. This activity is commonly regarded as free, that is, not forced or predetermined. The source of the will's freedom is difficult to determine, but it seems to be based in the fact that the will is the appetite that follows the intimations of reason. Because reason can see several alternatives that are equally feasible as means of reaching one end, the will has the freedom to elect from among them. Free will is thus the ability manifested in a human being's voluntary activity of choosing or not choosing a particular good when this is presented by the intellect. Such voluntary activity is also called free choice or free decision (Lat. *liberum arbitrium*).

The will parallels the intellect in its mode of operation: just as the object of the intellect is the true, so the object of the will is the good. On this account the will can be attracted to something only insofar as the thing is presented to it as a good. A good that can satisfy only to a limited extent is called a particular good, whereas one that can satisfy in every conceivable way is called a universal or supreme good. Now it is traditionally held that the human will is determined by nature to seek whatever it recognizes intellectually as the universal good. That is, it *must* seek, or cannot not seek, a good that is supremely good and contains no admixture of evil. If this is so, then freedom of choice is exercised only with regard to objects recognized as particular goods. A person is not determined to these, because goods that are particular can always be viewed in two opposing ways: they may be seen as good, i.e., according to the proportionate good they possess when compared to the universal good; or they may be seen as lacking in good, i.e., to the extent that they lack goodness when measured against the universal good. Thus, any finite good can be considered under the aspect of desirability or undesirability when compared to the universal good; as desirable, it can attract the will, as undesirable, it cannot. Not being determined or necessitated by such a good, the will remains radically free to choose it or reject it.

Among the powers of the human soul that influence choices of the will the most important is obviously the intellect. The will is urged toward anything that is understood to be in some way satisfying; such understanding is a function of the intellect. Despite this contribution of the intellect, since understanding of an object is a limited good for the person considering it, he or she may refuse to acquire a fuller understanding. Because of this, people may be attracted toward objects that here and now they consider good, whereas a more complete understanding of the same objects would have presented them as undesirable. The will can also be affected indirectly by objects of the sense powers, insofar as such objects are presented with a vividness rarely found in intellectual activity. Sense impressions and physical states, as a consequence, can strongly influence intellectual deliberation and choice.

The acts of the will are often called by the same name as the emotions of the sense appetites, namely, love, hate, desire, fear, anger, and so on. These, however, are not the will's proper acts. The proper actions of the will are to intend an end, to elect the means to accomplish it, and to command the actions that execute it. These are best understood when they are seen in their complex interplay with the actions of the intellect that go to make up the distinctively human act. Within the latter's various components, different intellectual actions evoke corresponding actions of the will, for what one wills depends on what one knows; on the other hand, each action of the will subsequently moves the intellect to a further action of knowing until the will is brought to rest in one of two possible outcomes: if successful, to an enjoyment of the end initially desired, or, if unsuccessful, to a sadness at not attaining it. A schema that illustrates this interplay, which, as can be seen, is mainly concerned with deliberation over ends and means, is shown in Table 1.

The items listed in this table exhibit the components of a fully conscious human act in dealing with a more or less complex practical situ-

Table 1. Components of a Human Act[10]

Actions of the Intellect	*Actions of the Will*
Concerning the End	
1. Apprehending the end	2. Willing an end
3. Judgment about an end	4. Intending an end
Concerning the Means	
5. Deliberating about means	6. Consent to means
7. Judgment about choice	8. Choice of means
Concerning Execution	
9. Command to execute choice	10. Use of powers to execute
11. Judgment of end attained or not attained	12. Enjoyment of end attained or sorrow at its nonattainment

ation. Not every human act a person performs involves all of these steps, but every such act in the practical order does involve seeking some end, a judgment and a choice of means, and a consequent decision to attain the desired end by carrying out the chosen course of action. Generally, of course, people do not proceed in their actions in the orderly way suggested by the steps numbered in the table. In difficult situations they often vacillate between one act or another on the part of the intellect and the corresponding act on the part of the will. But the numbering of the steps, evenly divided as they are between intellect and will, serves well to manifest the intimate connection between these two powers in the genesis of a human act.

The schema also enables us to analyze human freedom in more detail and see, more precisely, what constitutes the free human act, spoken of above as free will. Actually a free act is not an act of the will alone but a joint product of intellect and will. It is exercised principally, though not exclusively, in steps 7 and 8 of the table—the judgment on the part of the intellect that is inseparably linked to the will's choice of means. The intellect, in the practical judgment of appropriate means (assisted by what is called conscience), presents its choice to the will in step 7. The will, on the basis of that choice, freely elects in step 8 to follow it or not, that is, to do or not to do what should be done in the given circumstances. It

10. This schema, while not explicit in the works of Aristotle, has been extracted by commentators from his writings, particularly the *Nicomachean Ethics*, Books 2 and 3 (1103a12–1119b19) and Book 6 (1138 b15–1145a12). It is more fully elaborated by St. Thomas Aquinas, *Summa theologiae*, First Part of the Second Part, questions 6–21.

is in the latter step that the freedom of the human act is ultimately and principally lodged.

The relationship between the acts of the will and those of the sense appetites is likewise complex. In Fig. 5.3 it is shown by a single arrow directed from the will (W) to the sense appetite (BR), but influences can be exerted in either direction. One can arouse the sensitive appetites deliberately by willing to think about and imagine the objects that stir them. Moreover, it often happens that a particularly strong act of the will produces a similar passion in the sense appetites, by a kind of overflow or redundance. In their turn, the sense appetites can exert considerable influence on the will. The freedom of the will, for instance, depends on the power of reason to judge a situation calmly, taking into account all possibilities. But when the emotions are strongly aroused, the power of reason often fails to judge carefully, and one is precipitated into actions one would not otherwise have performed. The emotions can fix the attention of the mind on the things that stir them and limit its capacity to reflect, thus indirectly limiting the freedom of the will. Morever, to act contrary to strong passions produces equally strong feelings of pain and sorrow, and rather than endure these, people often consent to things they would otherwise reject. Thus, although the will is free and in supreme command of the human act, in practice it is often restricted in its freedom by the sense appetites.

5.6 Human Nature in Action

From this account of the will it may be seen that human nature responds differently than do other natures to influences exerted upon it. Inorganic natures either follow their natural tendencies when impediments are removed or react in quite predictable ways to external forces. Plant and animal natures do likewise, though their possibilities for self-development and self-preservation under varying circumstances make their life activities and behaviors far less predictable. Still they are very much predetermined in their modes of acting and reacting to stimuli and the environment in which they live. But human beings, through their powers of intellect and will, can react to external influences in almost unlimited ways and can initiate activities that vary over the widest scale possible, from those that are perfective of themselves and the human species to those that are abusive or destructive of other natures as well as their own.

The latter possibility notwithstanding, nature in general is not only an internal principle of characteristic activity but a perfective principle as well. On this account it would seem that, the more one studies a nature or a natural kind, the more one can appreciate how it should act or be acted upon to attain its proper perfection. What this suggests is a program that discerns in nature norms for behavior and so attempts to bridge the gap between being (*esse*) and action (*agere*) by invoking an objective standard, namely, the nature that is the root source of the action being studied. In the context of human action, this may be thought of as bridging the gap between the "is" and the "ought," between *theoria*, a speculative insight into human nature, and *praxis*, a practical knowledge of how individuals should act in accordance with that nature to achieve their proper perfection as human. Such a project was behind Aristotle's writing of his *Ethics* and his *Politics*, and it still motivates the search for what have been referred to in Sec. 5.3 as the moral sciences.

Moral sciences have been characterized as practical sciences, sciences concerned with knowing as ordered to acting or doing, and their concern is not with man's entitative perfection as already discussed but rather with an operative perfection, a perfection in *praxis*, which is the goal of disciplines concerned with practice. The goal of any science is truth, but that of a practical science is truth of the special type known as practical truth. This has already been mentioned, but now it requires further explanation and exemplification. Since two other practical sciences, namely, engineering science and medical science, are perhaps more easily recognized as sciences than are ethics and politics, our first illustrations will be taken from these disciplines. In the light of their discussion, we shall then move to a consideration of the operative aspects of the moral sciences, for these show human nature in action at a more basic level than do the other practical sciences.

Engineers work mainly with the inorganic natures discussed in Chap. 2. They investigate the forces and potentials found in such natures, not primarily to understand them, as might a physicist or a chemist, but rather to harness them, to channel them in the right direction, so to speak, to produce artifacts that serve the needs of man and society. Although an engineer might personally be interested in theories of electron flow through semiconductors, for example, his knowledge as an engineer is not measured by how good a theory of such flow he can formulate but by how well he can design and produce, say, a reliable computer. The practical truth of engineering is seen in its products: the suspension bridge, the space shuttle, the video cassette recorder. All of these are singular operables, whether a single one happens to be made or a million. Each must not only come to be, that is, be produced efficiently and cost effectively, but each must also function properly over its projected lifetime. Obviously creativity and ingenuity are part of the engineer's craft, because engineers are not predetermined to a given pattern, as beavers might be in building a dam or birds a nest. But creativity aside, engineering knowledge still consists in knowing the right thing to do—the *recta ratio* that lies behind the construction, operation, and maintenance of the engineer's creation—to assure the attainment of the goal embodied in the material artifact that is to be produced. Engineers must also know the mechanical, electrical, and other arts that might be necessary to produce that artifact. When they have this complete knowledge of causes and set correctly in motion the chain of events that produce the intended object, they have attained the practical truth at which engineering science aims and may be called good engineers.

What engineers attempt to do with inorganic natures has obvious parallels with what health practitioners attempt to do with organic natures. Here we will take health practitioner to mean not only physicians and surgeons but horticulturists, foresters, and veterinarians as well. All of these must possess detailed knowledge of the organ systems and the powers activating them in the organisms with which they work. No speculative truth available to the botanist or the zoologist falls outside their purview, and yet they cannot rest satisfied with such theoretical knowledge alone. They must grasp the natures of the plants and animals in their care and then give whatever assistance they can devise to bring the organisms to proper, healthy functioning. They spend much of their time diagnosing malfunctions or dysfunctions, for these must be understood if correct functioning is to be restored. But the measure of their truth or knowledge is not what they *know* about functions or dysfunctions, but rather what they are able to *do* with them to restore an ailing organism to health. They too must possess knowledge of causes that can be set in operation, not only by themselves but by the technicians associated with them, to restore health to the degree that this is possible. When they do so, they attain practical truth and are good physicians, veterinarians, etc. Not that they themselves make the organism healthy—that is the work of nature. What they do is assist nature by removing impediments to proper operation and by supplementing the resources available to the organism so that it may perform its life functions once again in healthy fashion.

To show this concern of physicians and engineers with proper doing

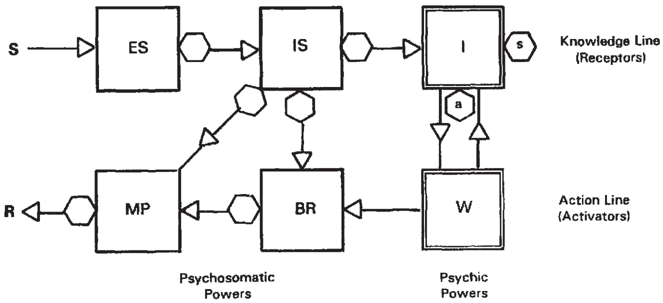

Fig. 5.4 Human Powers in Operation

or acting as opposed to mere knowing. Fig. 5.4 redraws the upper portion of Fig. 5.3, only now labeled somewhat differently to indicate the main cognitive and appetitive human powers and how these function in the "knowledge line" and the "action line" respectively. The two lines are also indicated as containing "receptors" and "activators," which rejoins the terminology used in the previous chapter. And the four powers to the left of the diagram have been labeled "psychosomatic" to indicate that their functioning is a bodily function (the "somatic" part), though it is controlled by a power of the soul (the "psychic" part). The two powers on the right, again shown in double outline, are now shown simply as "psychic" powers. The point of this is to indicate that they are immaterial powers to a much higher degree than the other powers, and so are sometimes referred to as spiritual powers, for reasons to be explained below in Sec. 5.8. They require no bodily organ for their operation, even though both make use of the brain and nervous system for the data of sense and for effecting the voluntary movements on which they jointly decide.

In Fig. 5.4 the knowledge line originates with stimuli (S) on the left and terminates with the intellect (I) on the right. Apart from the three sets of cognitive powers, the line itself is perfected when the powers of sense and perception are healthy, as signified by the hexagons attached to the external (ES) and internal senses (IS) and the arrows connecting them. The intellect is similarly perfected when it possesses various intellectual habits or virtues called sciences, indicated by the hexagon inscribed with the letter "s." What is now intended by that letter is not a single science, in the sense explained above in Sec. 5.3, but an ensemble that would go to make up the speculative part of the training of an engineer or a doctor—for example, the pure sciences of physics, chemistry, biology, and anatomy.

The action line of Fig. 5.4 is more complex, if only for the fact that it is dependent on the knowledge line and is influenced by it in various ways. It starts with the will (W) on the right and terminates with one or more actions or responses (R) on the left. The first influence from the knowledge line is that originating in the internal senses (IS) and going down to the left to the motor powers (MP), say, to produce a reflex or autonomic reaction. A second influence is shown by the path connecting the inner senses with the sense appetites (BR), illustrating the case in which something perceived elicits an emotional response that prompts the knower to action. This is how brute animals respond to their environment, and, provided their instincts are good and their reactions healthy, it is sufficient for the activities they require for survival. With humans the case is different, for knowledge responses in their case come from the intellect (I) rather than from perception alone. When responses come from the intellect, in the distinctively human act—one whose components involve in varying degrees the actions shown in Table 1—they are mediated to the emotions through the will (W), the power of choice and personal decision. It goes without saying that humans are animals and can act like animals, short-circuiting the path through the intellect and will. But reasonable and voluntary activity is what is normally expected of the human being.

In the bridge between intellect and will in Fig. 5.4, an operative habit labeled "a" has been added to the entitative habit "s," and a second arrow, directed upward from the will to the intellect, complements the one going in the opposite direction. The point of the two arrows is to stress the interplay between intellect and will that is normally required for a fully human act. The "a" again stands for art or technique (*technē*), the "know how" that applies knowledge to practice and points out the right thing to be done, here and now, to achieve an intended result. What is intended by this is the engineer's professional training and the doctor's clinical training—not pure science or theoretical preparation, concerned with universals, but the practical kind of knowing that applies directly to singulars, the concrete operables with which both professions are concerned. To refer to such operating knowledge as art or *technē* is not to remove it from the sphere of science. It is merely to place it in the realm of the practical sciences—sciences concerned with knowing "in order to do" and, in the final analysis, with "doing" more than with "knowing." A similar component, to be sure, is found in all the arts and crafts, from the art of politics and the art of rhetoric to architecture and the fine arts that make our world a more beautiful place to live in.

5.7 Operative Perfection

One may now ask the question, and it has been asked for centuries, whether there is a kind of knowledge that enables one to become, not a good artist or a good engineer or a good doctor, but simply a good person, a good human being precisely as human. Attempts to answer that question give birth to the special discipline known as ethics or moral science. The art of living well, that is, of living reasonably and bringing all of one's natural powers to their proper fulfillment, is the basic concern of ethics. Like engineering and medicine, this is a practical science. As Aristotle conceived it, it examines the ways in which one's operative powers can be habituated to act rightly, that is, reasonably, in the difficult situations with which one is daily confronted. For Aristotle this discipline has three components: ethics simply, which regulates how the individual should act to achieve his or her personal perfection; economics or social ethics, which addresses itself mainly to problems of the family and how its members can attain their proper well-being; and politics, which has a similar concern for problems of the state.

The basic insight behind these disciplines is that a person's natural powers can be perfected by operative habits in the action line just as they can by entitative habits in the knowledge line. Operative habits are acquired through repeated activity: if they advance a person's good and make him or her good, they are called virtues; if they do the opposite, they are called vices. The ensemble of virtues and vices one has acquired is usually referred to as character. Through daily living, people develop skill and personality traits; they also develop character, and they do so whether they consciously intend it or not. Virtues, or good habits of acting, are acquired through repeated actions moderated by right reason. Human beings develop a good character by cultivating what are called the cardinal virtues: prudence, justice, courage, and moderation.[11] These become "second natures," as it were, habituating those who possess them to act reasonably, i.e., to control their natural appetites and to give to others their due. In this way they become good, and so more fully human. Those who fail to acquire virtue, on the other hand, say, by being

11. They are called "cardinal" from the Lat. *cardines*, meaning hinges, for they are the hinges on which well-balanced living turns.

repeatedly unjust in their dealings with others, inculcate a character defect and to this extent are stunted precisely as human.

Ethics. The schematic diagram in Fig. 5.5 repeats that in Fig. 5.4, except that it now indicates the operative habits that bring one to personal perfection through rational and voluntary activity. Here the unlettered hexagons continue to represent health, but lettered hexagons have been added specifically to indicate the four cardinal virtues.[12] The letter "s" still represents the intellectual virtues of the speculative sciences, but the letter "a" that stood for the practical virtue of art has been replaced by the letter "p", standing for the moral virtue of prudence. Prudence is a habit of the practical intellect, that is, of the functioning of the intellect that looks toward the will, and it is also referred to as right reason (*recta ratio*). It enables one to choose wisely and well, to determine the correct course of action to pursue in the various circumstances met with in day-to-day living. It is concerned with subject matters that may pertain also to the other virtues, judging the mean between excess and defect, say, in matters of eating and drinking. Justice (j) is a habit of the will that inclines its possessor to render to others their due. Moderation (m), sometimes called temperance, controls the impulse emotions and disposes a person to be temperate with regard to food and sex. Courage (c), another term for fortitude, also addresses the emotions, but its function is to control the contending or aggressive emotions, guarding against excessive anger, fear, or despair. The individual whose intellect is perfected by repeatedly making prudent decisions, whose will is disposed to be just, whose emotions are under the control of intellect and will through courage and moderation, is said to have a good character. Character formation is thus nothing more than the process of acquiring moral virtues such as these and then habituating oneself to the type of action that is conformable to their possession and continued retention.

It may be noted that Fig. 5.5 is not intended to replace Fig. 5.4 but rather to represent human perfectability at its most basic level. The engineer or the doctor is first a human being and then a professional person. To apply the adjective "good" to such a person is somewhat ambiguous, for the goodness might apply to the person or to the actions he or she performs in a professional capacity. Special moral problems are also encountered in the exercise of the various professions in the present

12. Vices are not shown in the figure, though they too are real operative habits. They would be the opposite or the absence of the virtues indicated, such as imprudence, injustice, immoderation, etc. On the basis of their presence and habituating influence, a person might be called a thief, a liar, an alcoholic, and so on.

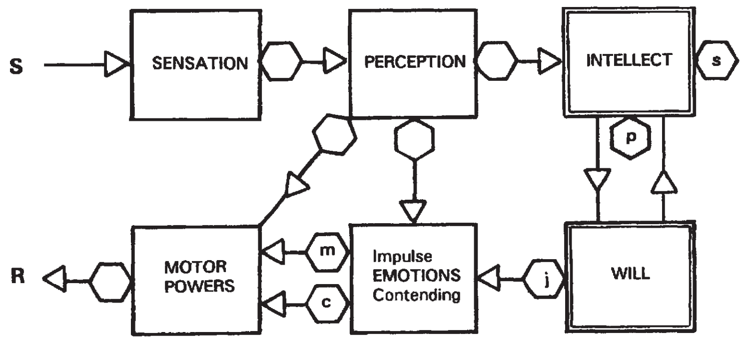

Fig. 5.5 Human Perfectibility

day, and these give rise to special fields of study within moral science, such as engineering ethics and medical ethics. But the findings at which these special studies arrive are intended to complement, not to replace, those of individual or personal ethics.

Society. Reasoning in this way, one can see how the concept of nature, and specifically that of human nature, can provide a norm—a natural and objective norm—for virtuous human action at the level of the individual. A further question arises whether it can also provide a norm for action in society and in the body politic. From the viewpoint of the persons themselves, the answer would seem to be obvious: good people, happy people, are those who have endowed their human natures with second natures, with intellectual and moral virtues, which bring them to their fulfillment precisely as human. But there may be additional ways in which society, and particularly its basic unit, the nuclear family, as well as the state, can contribute to human perfectibility, and these remain to be addressed.

Human beings are never completely self-sufficient: they come into the world dependent on parents, grow up within a family context, and require the additional resources of city or state to reach intellectual and moral maturity. Family and state, in one form or another, thus seem practically necessary for the development of a rational being: an *animal rationale* is by nature and instinct an *animal sociale*, and *homo sapiens* cannot help but also be *homo politicus*.

The family is obviously the first support system for human development. Mother and father are necessary to bring offspring into the world, and they are the normal requirement for providing nurture and sustenance during its early years of growth. Food and shelter are required for the proper development of organs and limbs, and both parents and the extended family are expected to provide these and the care their provision entails. Even more important, however, is growth in character, in learning not only to speak but to tell the truth, in practicing how to moderate one's appetites, in coming to recognize the rights of others and giving them their due. The community, and particularly the school, can provide assistance in such character formation, but the primary responsibility resides with the parents, with both mother and father, who must give long and devoted attention to the task if they would achieve its goal.

Politics. Does the body politic, over and above the family, have any essential role to play in the development of virtue? The question is difficult to answer, but a reasonable response can perhaps be gleaned from Aristotle's teaching in the *Politics*, particularly in the way he saw this work related to his *Nicomachean Ethics* and its preparatory treatises. For Aristotle, the *Politics* treats the second half of a subject matter whose first half is treated in the *Ethics*: both constitute the science of human affairs, of man's good and happiness. Such happiness consists in a certain manner of life, a life of virtuous activity, which inevitably is shaped by one's social environment—the laws, customs, and institutions of the community to which one belongs. The sense of Aristotle's statement that man is "by nature a political animal" is that humans develop their full capabilities in a society only when that society is rightly organized for their welfare. Once one knows in what manner of life human fulfillment is to be found, then and only then can one inquire into the form of government and the various social institutions that will enable it to be secured. It is this latter inquiry that raises questions about the constitution of the state, with which the *Politics* is principally concerned.

Politics, like ethics, is a practical science. Indeed, it is the supreme practical science, because it has for its aim human welfare and happiness as a whole. It is based on the premise that human beings are free and are capable of governing themselves, but it also recognizes that they are limited in this self-government because they are produced by nature and can perfect only the nature they have. The self that is involved in self-government is really the second nature or character one has developed, and this is determined by the virtues one has succeeded in inculcating. These, the cardinal virtues, here become the political virtues: prudence, justice, courage, and moderation. If all people possessed these virtues, government would be a very simple matter. The fact is that they do not. And so politics cannot deal with the ideal, utopian state; it must address itself to very refractory material, to man's common condition. In its practicality politics must adapt practical reason, and the laws that attempt to embody it, to meeting the conditions in which ordinary humans usually find themselves.

Since such conditions make full attainment of virtue extremely difficult, human law cannot forbid all vices, from which good people abstain, but only the more grievous ones, from which most people should be able to abstain. Chief among these are the vices that prove injurious to others, those involving injustice that make life in society difficult, if not impossible. Here an important difference should be noted between the political order and the moral order. The purpose of law is surely to make people virtuous, but the good that the law attempts to achieve is the human good of a multitude of persons, most of whom are deficient in virtue. For the common good of the state, then, it suffices that citizens be simply virtuous enough to obey its laws. Yet the virtuous performances of virtuous deeds would seem to be the end at which lawgivers aim. The political order directs itself to a common good predicated not on force or fear of the law, but on a free advance of its citizenry to the possession of virtue. Law can provide an extrinsic help, but the common good is attained only when an entire people develop a sense of justice, moderation, and responsibility as they attempt to bring their individual natures to proper fulfillment as human.

From this overview of the virtues, both speculative and practical, with which the human soul may be perfected, we may gain some appreciation for the tremendous gap that separates the human form from other natural forms in the organic and inorganic realms. Not only can the human form take care of bodily or psychosomatic activities as found in plants and subhuman animals, but through its power of intellect it is capable of a life of its own in the world of ideas, grasping in speculative sciences such as mathematics concepts that reach to infinity, and seeking in practical sciences such as politics a wisdom that aids others and directs them to their perfection as human. Human beings are thus capable of being perfected both entitatively and operationally, the first with habits for healthy functioning in mind and body, the second with moral and political virtues that enable them to reach their complete human fulfillment.

5.8 Intimations of Metaphysics

In the opening chapter, within the context of the causal model there being explained, we raised questions about the ultimates to which one may come in the consideration of material, efficient, and final causality as applied to the world of nature. With regard to material causality, the type of causality that seems most of interest to physicists in the present day, we entertained the Aristotelian concept of protomatter, the basic substrate that underlies all changes in nature and on that account is itself unchanging. Similar to the modern concept of mass-energy, protomatter is incorruptible and capable of infinite duration, and was so regarded by Aristotle.[13] In the sphere of efficient causality we were led to speculate about the agencies present in nature, inquiring whether there might be cosmic agents that serve to explain gravity and to direct the course of evolution, perhaps akin to the First Mover with which Aristotle concludes his *Physics*. And in the order of final causality we raised questions about the ultimate goal to which nature tends, thus joining the problem of its possible origin from nothing (*ex nihilo*), that is, its creation, to the existence of some unknown Omega Point that some day could bring its end. While we raised these questions, we did not attempt to answer them, for to do so we would have had to pass beyond the sphere of natural philosophy to another science, one that deals not with material being or with quantified being, as do natural science and mathematics respectively, but with unqualified being, with being precisely as such (*ens ut ens est*.) Only such a science, a science "beyond physics" and called metaphysics (*meta-phusika*) on that account, is capable of addressing the problems of immaterial being and of infinite duration, to which such questions inevitably lead.

A similar concern arises at this point about the human soul, for in his treatment of it Aristotle suggests that it, or its power of intellect, might in some ways be immortal and eternal.[14] His speculation about this has provoked extensive commentary throughout the centuries, for it focuses attention on an aspect of the human soul already referred to, namely, its special kind of immateriality that warrants its being called a spiritual soul. The sense of this expression may be gathered from Fig. 5.4, wherein the intellect and will are labeled "psychic powers" to differentiate them from the psychosomatic powers that energize organ systems within the human body. Since these psychic powers have operations that are essentially independent of the body, namely, understanding and willing, they possibly can survive the death of the body and continue on with a type of immaterial or spiritual existence. The mode of existence of the human soul would then be that of subsistent forms, what Aristotle spoke of as "intelligences" or "separated substances," known in other contexts

13. *Physics*, Bk. 1, ch. 9 (192a28)
14. *On the Soul*, Bk. 3, ch. 5 (430a23–24)

as angels or spirits. Being separated from matter and thus simple forms—that is, unlike sensible substances, which are composites of matter and form—subsistent forms cannot corrupt or cease to be. Once in existence, as simple and lacking components, there is no way they can decompose. In such a state the human soul would be immortal, and in this respect quite unlike other natural forms.

Despite the incipient metaphysics to which a fuller examination of subsistent forms might lead, the fact that the human soul is clearly a natural form when it first comes under scrutiny suggests that we conclude our examination of human nature by investigating its ambivalent status as both a natural form and a subsistent form. We propose to do so by explicating further the senses in which the two key terms, immateriality and simplicity, may consistently be applied to the human soul.

To say that the human soul is essentially immaterial is to say that matter does not enter into its composition and that it is independent of matter for its existence. In some meanings of immateriality these two characterizations do not apply. For example, the natural forms of sodium, geranium, and squirrel discussed in previous chapters are immaterial in the first sense but not in the second. Matter does not enter into the composition of such forms, and in this sense they are immaterial; yet they are dependent on matter for their existence, and in that sense they are material. The forms of sodium, geranium, and squirrel cannot exist without the matter they inform. Some natural forms are therefore material forms, even though matter does not enter into their composition. As opposed to these natural forms, the human soul is essentially immaterial because both of the noted characterizations apply to it.

The claim that the human soul is essentially immaterial may be argued as follows. In all physical changes, both substantial and accidental, the forms that are received are individual forms, because the subject that receives them is individual matter.[15] An individual form is a form that is one, countably one, among several of the same kind. A kind, considered as such, for example, squirrel, is neither one (countably one) nor more than one. Squirrel can be one or many only if found in a divisible entity in such a way that its actually being divided yields a countable or numerical plurality. In the physical universe such a divisible entity is extension or, more generally, dimensionality. In virtue of these, matter or mass-energy can be divided into diverse parts, each of which may be counted as one—for this is what is meant by "individual matter"—and into each of which, through an appropriate natural process, a form of

15. See Secs. 1.8 and 2.6 above.

some kind can be introduced. The possibility of a number of squirrels depends upon each individual squirrel having the same natural form, with that form also existing in a subject that is quantifiably distinct from other like subjects and thus countable.

Therefore, in the realm of physical changes, whether substantial or accidental, the forms received are individual forms, because the recipient is individual matter. The same thing is to be noted in the realm of sensitive activity. The sensible form received into a sense is received into a bodily organ, such as the eye, an organ that is three-dimensionally quantified and localized within the seeing organism. This explains why the intentional form that is received is an individual form. Extending the example, if the recipient of any form is individual matter, the form received is an individual form. Therefore, if human beings can discover in an examination of their knowing experiences forms that are *not* individual forms, it will follow that they possess a knowing power that is not the power of a bodily organ.

It is not difficult to discover such a form, for the human soul performs the activity of understanding. To understand is to receive the intentional forms or natures of things absolutely or universally, that is, as separated from, or abstracted from, their individuality.[16] For example, to understand "squirrel" is to have grasped this, namely, a small organism composed of flesh and bones and animated by a distinctive natural form—but understood absolutely and with no qualifications, and thus as applicable to any squirrel whatever. Existing squirrels are individual squirrels: each squirrel is something composed of this particular flesh and bones and its own animating form. It is the presence in the existing individual of quantified or dimensional matter, actually circumscribed to being just so much, that accounts for its being an individual. But a person's understanding, that is, his or her intellectual knowledge, of what it is that he or she attaches the word "squirrel" to is simply this: an object composed of flesh and bones and animating form. The intentional form that grasps this object is unqualified and universal: it is unqualified in the sense of not being circumscribed as "so much," or that "this particular" or "that particular" are not included in it, and it is universal in the sense that it applies not to any one squirrel but to each and every squirrel that may ever exist.

Despite the fact that each human soul is an individual soul, therefore, because it receives intentional forms that are unqualified and universal, it cannot have matter as a part of what it is and thus matter does not en-

16. See Sec. 4.5 above.

ter into its composition. For it is clear that what is received into something is limited by the very capacity of the recipient. Since the human soul, in knowing what things are, receives the intentional forms of things absolutely and universally, that is, since its mode of reception in intellectual knowledge is absolute and universal, the human soul must lack any principle of limitation such as matter and therefore must be essentially immaterial.

Moreover, if the human soul were composed of matter and form, it would follow that the forms of things received in knowing would be received into it as individuals, as is the case in sense knowledge and in physical changes generally. The same result would follow if the intellectual soul were held to operate through some bodily organ, say, the brain, in the way in which the power of sight operates through the bodily organ that is the eye. The bodily matter of the organ would individualize the form received. On this accounting the human soul must be totally free of matter: not only does it not have matter as part of what it is, but it neither exists nor operates with a dependence on matter.[17]

And yet this essential immateriality of the human soul must be understood properly. In itself its immateriality is complete, but in relation to the body, since it is the natural form of the body, its immateriality can be said to be partial. As the natural form of a living body, and as explained in the opening parts of this chapter, it is the source of vegetative and sensitive activities, and these take place with a dependence on the matter of the human body. Thus, the human soul has activities, hence powers or parts, that are material in the sense of being dependent on matter. In some of its parts, therefore, the human soul is dependent on the body. But in its intellectual and volitional parts, in those that are distinctively human, it is independent of the body.

This relationship to the body also casts light on the sense in which the human soul may be said to be simple. In essence, the soul is simple because it is not composed of matter and form; considered quantitatively, it is also simple because it is not composed of quantitative parts. Nonetheless it does have power parts (Sec. 3.7) through which it operates, and so it can be said to be dynamically composed. That is, it has a multiplicity of parts or powers that are ordered to a multiplicity of life activities. Some of these powers, as we have seen, can further be perfected by habits or virtues, and these are additional qualities that inhere in the soul. Thus to say that the human soul is simple is not to rule out its qualitative perfection. But a qualitative composition of this type is very

17. See Thomas Aquinas, *Summa theologiae*, First Part, quest. 75, art. 5.

different from an essential or a quantitative composition, and is quite consonant with its subsistent and spiritual nature.

This brief consideration of the immateriality of the human soul may serve to illustrate the difference between natural philosophy and metaphysics. Metaphysical questions are fascinating, but the language required to deal with them is quite different from that usually employed by natural scientists, and it is not really necessary for the understanding of nature we are proposing in this volume.[18] From what has been said, however, it should be possible to gain some idea of the human soul and to see how, as a natural form, it differs from other forms discussed in earlier chapters. In many ways human nature is the supreme achievement of the cosmos, the only form joined to matter that can reflect on all the works of nature, gain an understanding of nature itself, and put that understanding to work, as "lord of the universe," to benefit its own and other natures. Perhaps metaphysical reflection can further reveal the special excellence of individuals of that species, human persons, with their own special dignity and spiritual prerogatives.[19] But our present interest is obviously not in metaphysics, but rather in a less lofty philosophy that can address problems arising in the natural and human sciences, namely, the philosophy of science. With the concept of nature now sufficiently elaborated for its required background, we turn our attention to that discipline.

18. In view of the difficulty of even broaching questions that are properly metaphysical without an adequate terminology, it is surprising how frequently physical scientists venture into speculation about God and the universe of spirit. Those who do so apparently are unaware that facility in dealing with the world of matter does not automatically certify one to deal with immateriality as it is studied in the science of metaphysics, the science that is literally "beyond physics," and thus outside their area of competence.

19. Just as we are not treating metaphysics in this volume, we are not entering into the even more complex subject of theology. It is possible, of course, to extend our line of reasoning into theology, as Thomas Aquinas did with the medieval Aristotle. One of the best treatments of that subject from the viewpoint of modern science is Benedict M. Ashley, *Theologies of the Body: Humanist and Christian*, Braintree, Mass.: The Pope John Center, 1985.

Part II. Philosophy of Science

6 Defining the Philosophy of Science

The first part of this volume has focused on the concept of nature. Using that concept it has ranged over areas of investigation that pertain to all the natural and human sciences, and thus it can rightfully lay claim to being a philosophy of nature. The question that arises from this claim is whether or not the philosophy thus elaborated may also be termed a philosophy of science. A negative answer to this question might be suggested by the fact that nature and science are two different things: nature is an enduring extramental reality, something that exists in a mind-independent way, whereas science is the product of mental activity, something that exists in a mind-dependent way. A positive answer might be suggested by the fact that nature *as known* is what gives rise to natural science, and therefore to know nature is basically the same as knowing the science of nature. On this accounting, the difference between a philosophy of nature and a philosophy of science would be that between an object of knowledge and the knowledge itself, and within a realist theory of knowledge, at least, the two would seem to be in some way identical.

Considerations such as these aside, in the present day the philosophy of science has taken on an autonomous character and would not be identified by its practitioners with the philosophy of nature or natural philosophy. Philosophers of science have their own academic status and their own literature, and in that literature one finds little reference to nature or the allied concepts discussed up to this point. Textbooks dealing with the subject are mainly anthologies, not systematic treatises, and they are concerned by and large with philosophical problems raised by modern science, such as the meaning of scientific concepts, laws, and theories; the logical structure of scientific explanation; and the methodology by which it achieves its results. And, although some philosophers of science look back in history to scientific contributions of earlier centuries, by and large their efforts are directed toward understanding recent science, particularly scientific investigations that are heavily quantified and make use of mathematical formalisms such as those found in quantum theory and relativity theory. A major concern is the problem posed by the nonobservable entities associated with such theories, called on that account theoretical entities. Since logical empiricism is the dominant philosophical orientation in the discipline, it is not surprising that doubts are frequently aired about the ontological status of these entities. Those who regard them as existing extramentally are called "realists," those who do not, "anti-realists," and there is surprisingly little consensus between the two.

By the very nature of the discourse in which they are engaged philosophers of science usually have had some formal education in science: the majority in the physical sciences or mathematics, a smaller number in the life sciences, and fewer still in the behavioral or social sciences. Their formation in philosophy is mainly in twentieth-century empiricist or analytical thought and in mathematical logic. Most have little detailed knowledge of the history of philosophy, being particularly weak in Greek, medieval, and Renaissance thought, taking their intellectual start instead from modern philosophers such as René Descartes and Immanuel Kant. Because of this, there is usually little in their background that would acquaint them with the Aristotelian concepts that structure the first part of this volume, or what these may be able to contribute to the solution of problems that interest them.

6.1 The Break with Aristotle

The break with Aristotle that occurred at the beginning of the seventeenth century was occasioned in part by the recovery of Greek texts in the Renaissance and the assimilation of these to the existing Latin and Arabic traditions that had flourished in the Middle Ages. Consequent on this influx, Aristotelian logic and methodology were brought to such a state of perfection in the late sixteenth century—particularly at the University of Padua and at the Jesuit university in Rome, the Collegio Romano—that claims can be made for the beginnings of modern science at those institutions. But they were not completely representative, and the various scholasticisms in which Aristotelian learning was by then encased became so cumbersome that it was difficult to teach it as a credible synthesis. By the early seventeenth century, when the young René Descartes went to study under the Jesuits in the French college of La Flèche, the course in philosophy had been so watered down that it had little appeal for his creative mind. So he became the first of the great simplifiers, applying the principle of universal doubt to what he had been taught and seeking to construct a competing synthesis on the model of mathematics.[1]

The most striking features of Cartesian philosophy are its subjectivism and its mechanism, both of which combine to give the entire system a rationalist cast. The indubitable principle on which this was erected was one Descartes found within himself, "I think, therefore I am" (*Cogito, ergo sum*). This enabled him to begin philosophizing without investigating the external world, by merely reflecting on his own thought. Wanting to maintain the spiritual nature of man against an encroaching materialism, he made a radical distinction between the human soul and the human body, so much so that they became for him two different substances. The soul or mind he dubbed a "thinking thing" (*res cogitans*) and the body, his own and all others, an "extended thing" (*res extensa*). Matter he disposed of by making it synomymous with extension, and local motion he saw as the only type of change required in the universe, thus dispensing with substantial change and all qualitative changes. Since he rejected the vacuum and saw the universe as a plenum, local motion was for him simply displacement; this inevitably required vortex motion—the return of other matter to the place from which previous matter had been displaced. From ideas such as this Descartes attempted to deduce laws of motion, and from these all of his physics. Although he performed experiments from time to time to resolve doubtful issues, he thought essentially as a mathematician. His main criterion of truth was the "clear and distinct idea" he perceived to be at the root of geometry, and on this he strove mightily to base all of human knowledge.

Even from this brief sketch it can be seen that Descartes overworked reason in laying new foundations for philosophy. While his rationalism appealed to many as an alternative to Aristotle, it soon provoked a simplification of a quite different and opposing type known as British empiricism. The main proponents of the new view were John Locke and David Hume. Locke saw that reason alone could not be the starting point Descartes had tried to make it, and he reverted to a more traditional

1. For documentation in this section see the treatments of Descartes, Locke, Hume, and Kant in the author's *Causality and Scientific Explanation*, vol. 2. Classical and Contemporary Science, Ann Arbor: The University of Michigan Press, 1974, pp. 5–75. This work is cited because it sketches the teachings of these philosophers on specific points where they are at variance with Aristotle.

teaching: all knowledge must begin with sensation. Sensations, or "ideas," as Locke called them, are units somewhat like atoms that the mind perceives and aggregates into complexes. The fact that this process yields qualities that constantly go together, and cannot be imagined to subsist by themselves, led him to postulate an underlying substrate or substance in which they must inhere. But, unduly impressed by the corpuscular philosophy, he then proposed that the real essence of substance consists in the configurations and motions of insensible particles that forever escape man's observational powers. On this account the mind has to content itself with the nominal essence, with what it discerns as the observed properties and relations of bodies. Thus it cannot know substance in itself, but only the idea of substance as captured in the nominal essence. With Locke, then, the Aristotelian concept of substance receded into the background, gradually to be replaced by the notion that material bodies are nothing more than clusters of accidents.

David Hume thereupon elevated Locke's sensations to a more exalted status: they became the exclusive source of human knowledge. Sensations for Hume are lively perceptions and ideas are merely fainter ones, so that, in effect, the senses are man's unique power of knowing. The senses, moreover, are incapable of discerning any necessary connectedness between the events they perceive. Like Locke, Hume was skeptical about the idea of substance, taking it to mean only "a collection of particular qualities." But whereas Locke was willing to count powers among qualities, Hume dispensed with these also, arguing that we can have no impression of any force or power by which an object would be constrained to produce an effect on another. He extended his skepticism still further to reject the traditional notion of causality, replacing it with a much weaker notion, that of causation. In his view, all that our senses can perceive are temporal sequences among events and constant conjunctions between them. Since we are unable to discern "necessary connections" in nature, on observing a repetition of similar instances we are led by habit or custom to expect its usual attendant. Hume retained the terminology of cause and effect, but the best that "causal" knowledge could achieve for him was discerning present or past associations of classes of events. This discernment would be powerless to guarantee any human expectations about the future. Hence, in the study of nature, induction would be an untrustworthy guide, the ground for achieving demonstrative knowledge would be removed, and the Aristotelian ideal of science or *epistēmē* would be itself unattainable.

In the century and a half that separates Descartes from Hume, substantial simplifications were thus made in what had previously been known as natural philosophy, with most of the concepts treated in the first part of this volume being called seriously into question. It remained for our next thinker, Immanuel Kant, to deliver the death blow to that discipline, but in a somewhat unexpected way. Rather than continue the work of simplification, Kant changed course completely and became the great complexifier. As is well known, the epistemological edifice he constructed is enormous and defies simple exposition. Suffice it to say that he followed Locke and Hume (and, of course, Aristotle) in holding that all of our knowledge "arises from" experience, but he departed from them in arguing that any universality and necessity found in such knowledge must be put there by our own knowing processes. This led him to make his famous distinction between phenomena and noumena—the latter the "intelligibles" hitherto regarded as the proper object of the intellect (see Sec. 4.8). Kant proposed that the phenomena, or the appearances of things, can be used to attain valid knowledge, whereas the noumena, or "things-in-themselves," are forever inaccessible to human reason. Once his solution was accepted, natural philosophy as traditionally understood became impossible and science inherited the only task that was left, that, namely, of collecting data and analyzing phenomena as these present themselves in human experience.

To summarize, the modern mind owes mainly to Descartes and Kant the present-day distinction between natural philosophy and science. From them it also received certain fundamental principles that underlie, either explicitly or implicitly, most present-day philosophies of science. The first is that the clear and distinct idea is the criterion of truth; acceptance of this view entails a view of science that is essentially mathematical in character. A second principle is that there can be no knowledge of things-in-themselves, i.e., of natures or essences; as a consequence of this, most philosophers of science profess a basic agnosticism concerning man's ability to know reality in anything but a superficial way. A third principle, most influential with positivists and empiricists, is that all human knowledge must begin in the senses and is ultimately incapable of transcending the sensible. Such being the case, metaphysics is a "transcendental illusion" and any consideration of God, immortality, and free will can lead only to antinomies, that is, to ultimate contradiction. Legitimate knowledge of the real world is reached by "the secure path of science," the path already charted by a mathematical physics like that of Newton. The sole task left for philosophy would then be that of accounting for such systematizations as we presently find in physics and mathematics.

6.2 Beginnings of the Discipline

To flesh out more fully what the projected intellectual labor was to entail we propose to survey in this and subsequent sections the main stages in the development of the discipline now known as the philosophy of science. We take as our starting point a philosopher and scientist who was acquainted with Kant's thought as well as that of his predecessors, though he did not subscribe to Kant's radical agnosticism. This is William Whewell, one of the earliest English writers to write at length on the philosophy of science, and, indeed, on a philosophy of science based on its history. Whewell offers the additional advantage that he located himself in the tradition of Francis Bacon and Isaac Newton, his fellow alumni from Trinity College, Cambridge, and also situated his philosophy with respect to two contemporaries, August Comte and John Stuart Mill, whom some might regard as co-founders of the discipline. In the spirit of Bacon and Newton Whewell insisted on the importance of induction for arriving at the principles on which science must be based and so consistently referred to the sciences in which he was interested as "inductive sciences." This explains the titles of his two main works, *History of the Inductive Sciences*, 3 vols. (London 1837), and *The Philosophy of the Inductive Sciences, Founded Upon Their History*, 2 vols. (London 1840).[2]

Whewell defines the ideal of a philosophy of science as "nothing less than a complete insight into the essence and conditions of all real knowledge, and an exposition of the best methods for the discovery of new truths."[3] Thus he identifies its scope as jointly epistemological, a study of the nature of scientific knowledge, and methodological, a study of the methods whereby such knowledge can be attained. The realization of that ideal, for him, can only depend on a review of the most certain and stable knowledge we already possess and on how truths we universally recognize as such have been discovered. The premise of his enterprise is that doctrines "of solid and acknowledged certainty" exist and that these make up what we commonly call sciences.[4] He distinguishes between sciences concerned with the material world and those based on thought alone, that is, unmixed with any reference to the phenomena of matter.

2. For further information on Whewell, and fuller accounts of the other philosophers with which this section is concerned, August Comte, John Stuart Mill and John Herschel, see *Causality and Scientific Explanation*, vol. 2, pp. 86–141.

3. *Philosophy of the Inductive Sciences*, vol. 1, p. 1.

4. Ibid., p. 2.

The latter he calls pure sciences and the former, inductive sciences, because it is only by induction that general truths can be obtained from particular observed facts. While mainly concerned with the physical sciences, Whewell had no intention of ruling out the human sciences, for he was convinced that a study of the material world would yield principles applicable in every department of human speculation. Nor did he rule out metaphysics, as Kant attempted to do, for the physical sciences in Whewell's view have a metaphysical aspect that is a necessary part of the inductive movement. For him, successful investigators achieve their results only by combining their metaphysics with their physics instead of keeping the two completely separate.

Whewell's warrant for beginning this study was the systematic success achieved by the sciences in his day, which he regarded as completely unparalleled in preceding centuries. Others before him had pointed out instances in the physical sciences that supported their views of the progress of knowledge, but his was the first work, he claimed, that was drawn from a connected and systematic survey of the whole range of physical science and its history. This feature served to differentiate his effort from that of his illustrious predecessor Francis Bacon. In the latter's day scarcely any of the sciences existed in developed fashion. Bacon only divined how sciences might be constructed, Whewell observed, whereas in his own time it was known how their construction had actually taken place. Many of the maxims in the *Novum Organum* thus turned out to be inapplicable. Whewell noted that Bacon himself could not make the technical parts of his method work, with the result that his contributions are forgotten among scientists. Yet he felt much obligated to Bacon for his teachings on induction, and he later reissued the first part of the *Philosophy of the Inductive Sciences* with a new title paying tribute to Lord Verulam, *The Novum Organum Renovatum* (1858).

In elaborating his philosophy Whewell had to face the Kantian problem of how necessary truths can be derived from experience, and in fact he adapted parts of Kant's solution by making the mind an active principle for their attainment. In his view the formative activity of the mind is what structures experience so that one perceives events in space, time, and causal sequence. It does so by way of the "fundamental ideas" that are appropriate to each science. The function of such ideas is not merely regulative, as it was for Kant, but constitutive, so that it yields valid metaphysical knowledge of the structure of reality. These ideas are not grasped by all, Whewell conceded, but they can be seen intuitively by those who work in the particular sciences. There such ideas can be grasped progressively and clarified through contact with reality, since consideration of the science's subject matter is necessary for their attainment and proper use. Whewell was especially insistent on the mind's ability to discern causal connections, maintaining that knowledge of causes is necessary for a true understanding of the universe.

Largely because of his concern with causal explanation, Whewell vigorously opposed Comte's positivism and his conception of scientific method. Predictably, he was critical of the law of the three stages, which regarded theological and metaphysical thought as preliminary to the scientific or positive stage. In the latter stage causal investigation was ruled out, since, for Comte, the objects of science are exclusively sensible facts and the laws or relationships that obtain between them. Whewell rejected Comte's stages on the ground that they had no basis in history and are contrary to sound philosophy. He also ridiculed the very notion of a positive philosophy, pointing out that Comte had concentrated on denials rather than affirmations and that his views were more negative than positive. He examined in detail the Comtian interpretation of Newton's gravitational attraction and characterized it as superficial. His own analysis of Newton, Whewell insisted, shows that metaphysical discussions have been essential steps in the progress of each science.

Three years after Whewell published his *Philosophy*, John Stuart Mill brought out his *System of Logic*, in which he acknowledged a heavy dependence on Whewell's *History* and his *Philosophy*, so much so that without their aid the *System* might never have been written. Mill's work, however, is quite different in orientation from Whewell's, being more traceable to Hume than to Kant and showing pronounced Comtean influences. Mill allowed that the search for causes was essential to the scientific enterprise, but he restricted his consideration of them to the phenomenal order and so defined cause in Humean terms. The general uniformity of the course of nature, for Mill, is an invariable order of succession between phenomena. In his system, induction is possible, and indeed Mill proposed his work as doing for induction what traditional treatises on logic had done for deduction, that is, provide rules whereby one might arrive at general propositions with certainty. But precisely how general propositions entered into his inductive process is problematic, for Mill regarded induction as the process by which we arrive at individual facts, not from universals, but from other facts that are particular and individual.

Whewell published a detailed critique of Mill's logic in 1849, concentrating on these points. He also entered into a controversy with Mill over the role of ideas or conceptions in Kepler's discovery of Mars's elliptical orbit. Whewell insisted that Kepler had to impose the conception of ellipse on the observed facts to make the generalization possible, whereas Mill maintained that the ellipse was in the facts before Kepler recognized it. As for Mill's inductive canons, Whewell pointed out that they were merely a reworking of Bacon's "prerogative instances" and that they were of little or no help to scientists, who would already have gone through steps such as Mill describes and would not need his labeling of them to make their discoveries.

In conjunction with this latter criticism of Mill, mention should be made of Whewell's friend John Herschel, the foremost scientist in early Victorian England, who had pointed out similar limitations in Mill's *System of Logic*. Apart from his work in astronomy, Herschel wrote extensively on the methodology of science. Though generally empiricist in orientation, Herschel rejected Hume's account of causation as habitual sequence and himself provided rules for discerning invariable connections between cause and effect. Like Whewell, Herschel subscribed heartily to Newton's search for the "true causes" (*verae causae*) of natural phenomena. Neither had any doubt that science progresses through the discovery of laws and causes, that from this results a cumulative growth of knowledge, and that there are no limits to what the mind of man can uncover in the process. Yet, somewhat paradoxically, it was Mill rather than Whewell or Herschel who exerted the greater influence on later centuries. The *System of Logic* soon became the standard textbook of logic in British universities and, by the latter part of the nineteenth century, was looked upon almost universally as the authoritative treatment of scientific methodology.

6.3 Critiques of Science

We pass quickly now to the early twentieth century, by which time a pronounced turn was beginning to occur in evaluations of science. Part of this was occasioned by the study of electromagnetism and the growth of energy concepts, particularly as advanced by the German physicist Hermann von Helmholtz. Part of it was owed to the emphasis on statistical reasoning, as seen in thermodynamics and in the writings of the British political economist William Stanley Jevons. Part of it came from the studies of the German-born philosopher Johann Bernhard Stallo, who spent most of his life in the U.S. critiquing the concepts and theories of modern science. All of these thinkers directed their efforts against the metaphysical pretensions of classical scientists, particularly in their arguments for the existence of atoms and molecules on the basis of insufficient empirical evidence. Each prepared in a different way for a movement known as empiriocritism, which included such distinguished names as Ernst Mach, Henri Poincaré, and Pierre Duhem, and which was the immediate predecessor of the philosophy of science movement in the U.S. and the U.K. Before coming to that, however, a few comments should be made about writings of a contemporary American, Charles Sanders Peirce, who, while not usually numbered among the critics of science, nonetheless exerted an influence on the movement that followed.[5]

The son of Benjamin Peirce, professor of mathematics and natural philosophy at Harvard University, C. S. Peirce is best known in philosophical circles as the founder of the distinctive American movement known as pragmatism. He also did extensive work in the philosophy of mathematics and in the philosophy of science, the latter being his preferred avocation. Unlike most scholars working in this field, Peirce was interested in scholastic realism and in the history of science, being aware of Galileo's use of *il lume naturale* (the natural light of reason) and comparing it with his own idea of abductive inference. The latter is Peirce's contribution to the problem of inductive reasoning and is somewhat similar to the demonstrative *regressus* used by Galileo, to be discussed in a later chapter. For Peirce abduction is the type of inference that yields an explanatory causal hypothesis from which one can deduce conclusions, which then can be tested against experimental evidence. The result of this testing he called an inductive inference or a retroduction. Peirce was aware that this type of reasoning admits of the possibility of error and so is unable to attain absolute certainty. Yet he was a firm realist in his convictions and was resolutely opposed to the nominalistic positivism being proposed in his day by Mach, Duhem, and the English statistician Karl Pearson.

Empiriocriticism. The main figure in empiriocritism is Ernst Mach, a physicist who wished to develop an epistemology that could be used by scientists in their work of criticism. Having studied scrupulously the methods employed and the conclusions to which classical mechanics had come, he was intent on showing the inherent limitations of both. Mach used positivist principles in his critique, and, being convinced that there is no profound truth beyond empirical data, effectively denied the possibility of metaphysics. Among his key works are *The Science of Mechanics* (1883) and *The Analysis of Sensations* (1886).

5. For further information on Jevons, Mach, Poincaré, and Duhem, see *Causality and Scientific Explanation*, vol. 2, pp. 166–180.

The principal points of the philosophy of science elaborated by Mach may be summarized as follows. The object of any science is sensation and sensation alone; science does not attain to any object distinct from subjective impressions. Sensations are not disconnected but are organized into constant groupings that are designated as "things." Thus, contrary to a realist epistemology, in which sensations refer to things, Mach's empiricism proposed that things are merely symbols of sensations. He thus conceived the task of science as one of analyzing sensations and their relationships so as to organize them into some type of synthesis. The aim of this synthesis is not theoretical, i.e., it is not to inquire into the causes and meanings of phenomena or to supply explanations for them; rather, it is simply practical. The end of science is to enable man to adapt himself, with a maximum economy of thought and effort, to the conditions that produce the sensations he experiences.

Mach admitted hypotheses into his science as temporary and useful aids—for example, to organize experimental data and to suggest new experiments. In his view one should never ask if hypotheses are true or false but only if they are useful. Similarly, laws for him are rules that can be used economically to replace a series of facts. Whenever possible they are to be expressed in mathematical formulas. On Mach's terms it is impossible to know laws of nature as extramental regulators of phenomena. Further, like his empiricist and positivist predecessors, Mach practiced the philosophy of science with an anti-metaphysical bias. And yet he did admit a certain congruence or agreement between natural events and the expectation of them attained through scientific reasoning. He thought that this required more than chance as an explanation, and he invoked a type of psychophysical parallelism as its underlying basis. Such an account was inconsistent with his positivist principles, and it left the way open for philosophies of science that would concede some validity to metaphysics.

Critique de la Science. Closely akin to empiriocriticism is the French movement known as *Critique de la science*, which flourished around the same time and whose foremost representatives were Henri Poincaré and Pierre Duhem. Both were more tolerant of metaphysics, though both were intent on keeping it completely out of their science. Poincaré was the preeminent mathematician, mathematical physicist, and astronomer of his day, whereas Duhem was a physical chemist and pioneer historian of medieval science, well known for his Catholicism at a time when anticlericalism was at its height in his native land. Though they came from different backgrounds and were motivated by different reasons, their views of science and its philosophy turned out to be quite similar.

Poincaré's philosophy, known as conventionalism, was set out in a series of works: *Science and Hypothesis* (1902), *The Value of Science* (1905), *Science and Method* (1909), and *Mathematics and Science: Last Essays* (1913). These may be said to epitomize the critique of science movement. Through the influence of Antoine Cournot and Émile Boutroux, Poincaré came to be convinced that science has no absolute epistemic value, particularly when based on its success in prediction. He felt that any explanation being used at a given time to account for future phenomena must ultimately give way to a better explanation. While conceding that scientists speak of their theories as true, he maintained that in actuality theories are not true but only convenient: they serve to simplify the work of scientists and provide them with an aesthetic picture of the universe. Nonetheless, Poincaré was opposed to the thoroughgoing empiricism of many of his predecessors, as well as the extremes of rationalism and scientism.

In working out the details of his system, Poincaré proposed a distinction between sciences that are merely rational and those that are empirico-rational. The merely rational sciences, the paradigm of which is mathematics, are for him free constructions of the human mind. The role of experience is completely extrinsic to their development, merely suggesting possibilities to them and providing instances for their application. The objects of such sciences are beings of reason (*entia rationis*). The relationships that obtain among these objects are expressed by axioms; these are freely postulated and implicitly define the objects and their properties. Yet they are not completely arbitrary. They must avoid internal contradiction and be at least convenient, that is, simple and adapted to the properties of the entities with which they deal. The empirico-rational sciences, on the other hand, are for Poincaré concerned with the objects of experience, with entities in the external world. Experience provides single facts, which the mind uses to ascend to the universal order by constructing hypotheses. Such hypotheses in his view are again not merely arbitrary: they must agree both with experience and with experimental laws. Still they are selected by "free convention," insofar as a great number of different possibilities may be excogitated to explain the same facts. For this reason hypotheses, like laws, should be said to be, not true or false, but more or less "suited" to describing phenomena.

Duhem assimilated the teachings of Poincaré and on them erected a philosophy of science that was influential, particularly in Catholic circles, at the beginning of the twentieth century. The main outlines of this are set forth in his *The Aim and Structure of Physical Theory* (1906, 2d ed. 1914) and *To Save the Phenomena* (1908). These must be read in the light of his historical studies, the most important of which are *The Evolution of Mechanics* (1902), the two-volume *The Origins of Statics* (1905–1906), the three-volume *Studies on Leonardo da Vinci* (1906–1913), and the ten-volume *The System of the World* (1913–1959). A prolific scholar up until his death in 1916, Duhem opened up pathways in the history of medieval science that are still being pursued in the present day.

Basic to Duhem's critique is his sharp distinction between two orders of knowledge, the one of philosophy and the other of science. Philosophy, which for him was essentially metaphysics, seeks the explanations, causes, and essences of things; the physical sciences do not. The knowledge the sciences provide is essentially symbolic: they do not explain phenomena, they merely represent or symbolize them. The difference between these two areas of discourse, as Duhem understood them, may be seen from the way he opposes laws of common sense to those of science. The laws that ordinary and nonscientific experience enables us to formulate, he states, are general judgments whose meaning is immediately apparent. When asked if they are true, one can usually answer with a definite "yes" or "no." If the answer is "yes," the law is recognized as true and is so for all time and for all men. It is fixed and absolute.

In Duhem's view scientific laws, those based on physical experiments, are quite different. They are symbolic relations whose meanings are unintelligible to anyone who does not know the theories on which the experiments are based. Since they are symbolic, they are never true or false; like the experiments on which they rest, they are approximate. Duhem further maintained that the degree of approximation of a law is relative to the experiments on whose basis it was formulated. While sufficient for the time being, progress in experimental methods will render them insufficient in the future. Thus a law of physics is both relative and provisional. Another aspect to consider is that it connects not realities but mere symbols, and situations can develop where the symbol no longer corresponds to the reality. As a result the laws of physics cannot be maintained except by continual retouching and modification.

No doubt Duhem's positions on these matters were influenced by his conservative views and his interest in protecting his religious faith against the inroads of a materialism based on science. In effect he placed the "perennial philosophy" of the Church beyond question, while according only a conjectural status to the advances made by modern science. But the wall of separation he introduced between philosophy and science met with approval in many educational circles, and its effects are still widely felt in the present day.

6.4 The Logical Construction of Science

Toward the end of the nineteenth century the evolution of mathematics led to another type of critique that was no less profound than that just dealt with. Of the many developments in that field, non-Euclidean geometry and set theory had the most significant impact on the philosophy of science. Both seemed to illustrate how statements once taken without question as simple presuppositions of mathematics are in fact not certain at all. They thus directed attention to the analysis of apparently simple concepts and to the axiomatic construction of systems. In set theory particularly, right at the end of the century, attention was drawn to new paradoxes, that is, contradictions derived by correct methods of inference from apparently simple and obvious assumptions. These resisted resolution to such a degree that the very foundations of mathematics seemed on the verge of collapse.

In close conjunction with this crisis came the growth of interest in formal logic, especially in the type known as symbolic or mathematical logic. Neither Descartes nor Kant manifested any interest in logic, and, apart from the work of Leibniz, very little was done in the field in the early modern period. Then, about the middle of the nineteenth century, two English mathematicians, Augustus de Morgan and George Boole, published works that gave a new direction to logical research. This was carried forward by the Italian Giuseppe Peano and the Germans Ernst Schröder and Gottlob Frege—especially the last, an exceptionally creative logician and philosopher. But it was not until Bertrand Russell made contact with Peano in 1900 and published his *Principles of Mathematics* in 1903 that philosophers, particularly those in English-speaking countries, took note of these investigations. The new discipline was placed on firm ground when Russell collaborated with Alfred North Whitehead to produce the *Principia Mathematica* (1910–1913), a work of monumental proportions that aimed to place all of mathematics on consistent logical foundations.

Logical Positivism. The impact of this work on the philosophy of science can be seen in the movement known as logical positivism, which developed in Vienna around the 1930s and continued the work of criticism inaugurated by Mach, Poincaré, and Duhem. By that time, through the writings of Max Planck and Albert Einstein, quantum theory and relativity theory had assumed tractable form and were presenting physicists with their own set of antinomies. The nucleus of the movement was a group of philosophers and scientists, known as the Vienna Circle

(*Wiener Kreis*), who met informally to discuss one anothers' problems. The circle included Moritz Schlick, Rudolf Carnap, Philipp Frank, Otto Neurath, and Herbert Feigl. More loosely allied to them were Hans Reichenbach and Carl Hempel, then working in Berlin, and Bertrand Russell and Ludwig Wittgenstein, centered in Cambridge, England. Also related to the circle was Karl Popper, who reacted against some of its teachings and pursued an independent career in London. The most important figures in the movement later found their way to North America, where they were variously known as logical positivists or logical empiricists.[6]

The founder of logical positivism is generally regarded as Moritz Schlick, one of Mach's successors as professor of the inductive sciences at the University of Vienna. Schlick's aim was not so much to develop a new system of philosophy as to inaugurate a scientific way of philosophizing. For him, as can be seen from his *Philosophy of Nature* (1936), philosophy is identified with the philosophy of nature, which he took to be the same as the philosophy of science. He conceived the task of science to be to obtain knowledge of reality, and that of philosophy to interpret scientific achievements correctly and to expound their underlying meaning. As he put it, scientists must persistently and indefatigably examine the correctness of their propositions and develop them into more and more securely established hypotheses. They alone can test the assumptions on which these hypotheses are based, for there is no specifically philosophical foundation on which such assumptions can be vindicated.

Philosophers of science are also concerned with scientific hypotheses, Schlick allowed, but in a way quite different from scientists. All natural knowledge is formulated in propositions, and the laws of nature are no exception; they too are expressed in propositional form. But the knowledge of a proposition's meaning is a prerequisite to testing its truth. Thus there are two tasks within the scientific enterprise: one concerned with ascertaining the truth of hypotheses, the other with understanding their meaning. The methods of science assist in the discovery of truth, those of philosophy in the elucidation of meaning. Thus the philosopher of nature takes on the function of interpreting the meaning of the propositions of science. He is not a scientist, but one dedicated to discerning the meaning of what Schlick called "the laws of nature."

Unfortunately Schlick went on to define the meaning of propositions,

6. For brief accounts of the work of Moritz Schlick and Hans Reichenbach, see *Causality and Scientific Explanation*, vol. 2, pp. 180–187.

somewhat simplistically, as their method of verification. Present at the meetings of the Vienna Circle where verifiability was being discussed—not only in the context of meaningfulness but also as a criterion of demarcation between science and metaphysics—Popper reacted vigorously to verifiability and argued for falsifiability instead as the better overall criterion. As he explained in his *Logik der Forschung* (1934), the proper empirical method is not one of verifying theories but rather one of repeatedly exposing them to the possibility of being falsified. Through the proper application of rules for falsification, he maintained, science would evolve, be self-correcting and progressive, and so dynamically approach the truth. In a later work, *Conjectures and Refutations* (1963), he proposed that the entire history of science could be viewed as nothing more than a sequence of conjectures, followed by their refutations, then revised conjectures, additional refutations, and so on.

These characterizations by Schlick and Popper of the respective tasks of the scientist and the philosopher of science may be said to have provided the positive inspiration for the philosophy of science movement in the pre-World War II era. Previous thinkers had pointed out the necessity of a reflective consideration of the work of science, but many of them had fostered a negative view of philosophy as this relates to science. Poincaré and Duhem had maintained, in effect, that science raises no philosophical questions and that it can provide no definitive answers to questions posed by philosophers. In these later formulations, however, philosophy was placed once again in closer relation to science. It was taken into partnership, as it were, and given the task of interpreting the symbolism of science, of discovering the profounder meaning that underlies its laws and theories.

Hans Reichenbach early advocated a relationship between science and philosophy similar to that proposed by Schlick. What was only implicit in Schlick's thought, namely, that philosophy is to be identified with the philosophy of nature, and the philosophy of nature with the philosophy of science, came to be explicitly stated by Reichenbach. Unable to conceive of any philosophical enterprise that did not base itself on the findings of science, Reichenbach consciously elaborated his "scientific philosophy," the main lines of which are set out in his *The Rise of Scientific Philosophy* (1951). As he explained it, since philosophy is dependent on science, this dependence should be a conscious condition of the philosopher's work: he should acknowledge that the nature of knowledge can be studied only through the analysis of science. Thus the philosophy of science subsumes within itself all that had previously been regarded as epistemology. Reichenbach was also insistent that there is no ontology, no separate realm of philosophical knowledge that precedes science. For him philosophy does not contribute any content to knowledge; it merely studies the form of knowledge as exhibited in the work of the scientist and examines all claims to validity. His scientific philosophy would therefore evaluate the findings of science as an ongoing enterprise. There could be no finality in a philosopher's results—the latter's only function would be to keep the world abreast of scientific progress.

Logical Empiricism. It was not long before imperial claims such as these, combined with the aggressive anti-metaphysical attitudes of Reichenbach's colleagues, gave a bad name to logical positivism. As the movement developed in the U.S. this label fell out of favor and those sympathetic to its program became known as logical empiricists, or as tolerant or nondogmatic empiricists, or simply as neoempiricists. Representative of the latter group is the American philosopher Ernest Nagel. Working within the framework provided by Schlick and Reichenbach, Nagel attempted a more systematic approach to the philosophy of science.[7]

By 1960 the growth in literature associated with logical empiricism had led to the application of the term "philosophy of science" to a heterogeneous collection of problems related in various ways to science. Textbooks of readings on the subject had also appeared. These discussed, among other things, problems relating to epistemology, such as the validity of sense perception; those relating to the genesis and development of scientific ideas, the nature of scientific laws and theories, etc.; and various logical problems relating to the axiomatization of systems, the justification of inductive procedures, and the confirmation of theories. From this listing one can see in a general way that the definition of the philosophy of science proposed by Whewell in 1840 had been remarkably prescient: the main efforts in the field over a period of more than a hundred years had in fact centered themselves around problems relating to epistemology and the methods scientists use to achieve their results.

Yet Nagel complained that the discipline so delineated was not a well-defined area of analysis, and so he preferred to concentrate instead on the logic of scientific inquiry and the logical structure of its intellec-

7. Nagel's work is discussed in *Causality and Scientific Explanation*, vol. 2, pp. 206–217.

tual products. In effect he would make the philosophy of science more explicitly a logic of science. He thus proposed a systematic exposition of these matters in three parts: the first would deal with the logic of scientific explanation, the second with the logical structure of scientific concepts, and the third with the structure of probable inference and the validation of inductive arguments. Only the first of these was ever published, however; this was *The Structure of Science: Problems in the Logic of Scientific Explanation*, which appeared in 1961.

The logical reconstruction of science envisaged by Nagel by this time had already achieved substantial results, and a firm consensus had begun to emerge among logical empiricists regarding the main theses being embraced within their version of the philosophy of science. The first of these relates to the language levels employed by scientists, the second to the logical structure of scientific laws, and the third to the logical structure of scientific theories. Because each of these in its own way came to be called into question in subsequent decades, a brief characterization of them may prove helpful at this place.[8]

With regard to the first, the language of science was seen as made up of a hierarchy of four levels: the lowest level is concerned with the primary experimental data on which scientific conclusions are based; the second level, with concepts extracted from such data and expressed in quantitative terms; the third level, with laws that express invariant or statistical relations among scientific terms; and the fourth, with theories or deductive systems in which laws appear as theorems. Within this language system, wherein instrumental data are at the bottom and theories at the top, each level is seen as an interpretation of the one below. The predictive power of statements also increases as one goes up the ladder. The three lower levels—data, concepts, and laws—may be referred to as "observational levels," and as such are differentiated from the top or "theoretical level," that of theories. They provide the ground against which statements at the top level are ultimately to be tested.

The transition from the first level to the second generally invoked Schlick's dictum that the meaning of a concept could be discerned from its method of verification, revised now to stipulate that that method be stated in operational terms. In other words, as proposed by Percy W. Bridgman in his *The Logic of Modern Physics* (1927), scientists attach values to concepts by the instrumental procedures they use in the labo-

8. Here we are following the exposition of John Losee, *A Historical Introduction to the Philosophy of Science*, 3d ed., Oxford and New York: Oxford University Press, 1993, pp. 184–187.

ratory to make measurements. If no operational definition could be attached to a concept, Bridgman had maintained that the concept has no empirical significance and as such should be excluded from scientific discourse.

The next transition was one of incorporating scientific concepts thus defined into generalizations or scientific laws and specifying the logical relations that should obtain between laws and concepts. In an important paper written in 1948, Carl Hempel and Paul Oppenheim addressed this problem by analyzing what it means to offer a scientific explanation for empirical facts. The solution they proposed is referred to as the covering law model.[9] In this model a scientific explanation is construed as an answer to the question "why?"; this is seen as a deductive pattern wherein the premises are a scientific law or empirical generalization together with an enumeration of the various conditions under which it is applied. The law is a universal statement explicitly or implicitly containing the quantifier "All," plus a series of observational terms. The conditions then enumerate the boundary conditions within which the law is believed valid and the initial conditions that obtain when the answer to the "why?" question is being sought. Accidental generalizations are ruled out on the ground that the generalizations used should be law-like or nomic (from the Gr. *nomos*, meaning law). This is usually understood to mean that they are not spatially or temporally restricted in scope but remain open for application to additional individuals or events. Some add the further requirement that genuine laws be able to support contrary-to-fact conditionals, thereby implying some type of necessary connection between the conditions and events covered by the law. They hold that, even though the specified conditions are not *de facto* realized, if they *were* realized, the event would necessarily occur.

The transition from the third to the fourth level was that from law to theory. A theory was usually differentiated from a law by the fact that, although both contain the universal quantifier "All" and observable terms, a theory additionally contains terms that designate nonobservables, that is, entities that escape observation by the senses. These are thought of as postulated or hypothetical entities and the terms designating them are known as theoretical terms. As formulated by Rudolf Carnap, a theory is thus an axiom system containing some terms that are undefined; since these cannot be directly interpreted in terms of empirical

9. For a detailed study of the covering law concept and its subsequent history, see Wesley C. Salmon, *Four Decades of Scientific Explanation*, Minneapolis: University of Minnesota Press, 1990.

evidence, the theory is only "a partially interpreted formal system." Carl Hempel and others have proposed a "safety-net" model of a theory that is somewhat similar. In it the axiom system is a net supported at critical points by connectors that anchor the net to terms in the scientific language referring to observables. Theoretical terms, unlike observable terms, cannot be defined operationally. Nonetheless they take their meaning from their place in the overall network and from the semantic or correspondence rules that tie them to observables.

Finally, theories understood in this way can be used to explain laws, again on the deductive model described above. Moreover, there are hierarchies among theories, with a few overarching theories being used to explain others. This gives rise to the problem of theory reduction—whether some theories, at least, are reducible to others, which can be regarded as more fundamental on that account. A related question has to do with scientific growth, namely, when one theory is replaced by another, whether the replaced theory can ultimately be incorporated into the one replacing it. If so, should one eventually be able to formulate a super theory that explains all the others, a grand unified theory or "theory of everything," it will obtain inductive support from all the previous findings of science. Would it not then supply the ultimate answers to questions about the universe? An affirmative reply to all these queries would bring to realization the ideal of a "unified science" expressed by Otto Neurath in the early days of the Vienna Circle: one science, presumably physics, would then provide the foundations for all of human knowledge.

6.5 The Historical Development of Science

A year after Nagel's *The Structure of Science* appeared, Thomas Kuhn's *The Structure of Scientific Revolutions* (1962) was published, and this marked a watershed in the philosophy of science movement. Ironically, it appeared as Volume 2, Number 2, of the *International Encyclopedia of Unified Knowledge*, with Neurath, by then deceased, still listed as editor-in-chief and Rudolf Carnap and Charles Morris as associate editors.[10] The logical reconstruction of science had already reached a stage where it could be formulated in terms that were well agreed upon

10. Some light is cast on Kuhn's relationship to Carnap and the Vienna Circle by G. A. Reisch, "Did Kuhn Kill Logical Positivism?" *Philosophy of Science* 58.2 (1991), pp. 264–277.

and could provide the basis for scholastic controversy. Paradoxes had occurred in the application of formalisms to physical problems, and these invited a variety of solutions. The justification of induction, the allied problem of law-like generalizations, the difficulty of dealing with powers or dispositional terms, and the reoccurrence of interest in causal efficacy and necessary connection, all had raised once again the specter of Hume and his unsolved difficulties. A particularly vexing problem for empiricists was the ontological reference of theoretical terms. Do they designate real entities or are they merely fictions that are useful in the scientist's work of prediction? If realism is the answer, then science is suggesting a transempirical element in knowledge that a radical empiricism had earlier ruled out as meaningless or forever unattainable.

Kuhnian Criticism. But none of these problems, oddly enough, was the precise target of Kuhn's criticism in his exploration of the structure of scientific revolutions. Put simply, his focus was on a striking anomaly: the logic of science, carefully developed as it had been, seemed quite at variance with science's history, and particularly with the fact of science's somewhat haphazard development and the time-to-time occurrence of scientific revolutions.

By training a theoretical physicist, Kuhn had earlier published *The Copernican Revolution* (1957), a work that, like *The Structure of Scientific Revolutions*, had grown out of his teaching an experimental college course in physical science to nonscientists and using an historical approach. This experience convinced him that there was a role for history in the understanding of science. Properly understood, he argued, history could produce a decisive transformation in the image of science then generally accepted, one that had come from science textbooks and their simplified accounts of the procedures and logical operations whereby science is produced. Previous to Kuhn's work, scientists had viewed their science as an objective and rational enterprise employing a methodology that eliminates subjective judgments and that ultimately contributes to a cumulative growth of knowledge. Philosophers likewise had consistently regarded science as a special type of critical inquiry—one productive of knowledge that is publicly verifiable, grows more or less continuously, and thus is essentially evolutionary in its mode of development.

As the titles of his works suggest, by concentrating on the revolutionary character of science as opposed to the evolutionary, Kuhn launched a frontal attack on this "cumulative growth of knowledge" thesis.[11] The burden of his analysis was to show that the larger part of scientific activity, what he calls "normal science," is essentially puzzle-solving within the context of paradigms or sets of rules that are accepted within a scientific community. At rare intervals, in his view, scientists break out of this normal pattern and institute a revolution. This is equivalent to retooling within the community and adopting a new paradigm that solves yet further puzzles. Through a series of such revolutions, however, there is not necessarily linear progress or cumulative growth. Scientific revolutions really amount to different ways of looking at things, like Gestalt switches. Thus one should be wary of regarding them as productive of new truths, or even of seeing them as tending asymptotically to objective truth as the limit of a knowledge acquisition process. Science, for Kuhn, is not evolutionary at all; it is basically revolutionary, ever changing, and not a stable body of knowledge to which additions are constantly being made by an evolutionary process.

The key to Kuhn's thesis is obviously the term "paradigm," which has gained wide currency from the use he puts it to. The term is difficult to characterize unambiguously, but it need not be defined in order to be recognized. Broadly speaking, it is a model solution to a problem that is commonly accepted within a scientific community, an insight into how the phenomena in any domain of experience should be explained. Related to the paradigm will usually be several theories that use one or more of its elements. Having adopted such a paradigm and its related theories, scientists proceed to work out all of its problem-solving implications. It is this activity that Kuhn characterizes as normal science. While normal science is going on, the paradigm that controls (and defines) it will itself be regarded as beyond question. Attempts to apply it to new areas may be criticized; they may be falsified, and even abandoned; but the paradigm itself remains unchallenged.

This state continues until sufficient anomalies accumulate for the scientific community to begin to question whether the paradigm under which it has been working is valid after all. When this happens, as Kuhn sees it, the science is in a period of crisis. In a crisis situation, scientists entertain for the first time the possiblity of abandoning the reigning par-

11. For an exposition and critique of Kuhn's argument, see the author's "Causality, Analogy, and the Growth of Scientific Knowledge," in *Tommaso d'Aquino nel suo settimo centenario*, 9 vols., Naples: Edizioni Domenicane Italiane, 1978, vol. 9, pp. 26–40, reprinted in his *From a Realist Point of View*, 2d ed., Lanham, Md.: University Press of America, 1983, pp. 213–227.

adigm and of investigating new ones. Should one of the latter turn out to be more successful in solving problems, a scientific revolution occurs. The new paradigm takes the place of the old, and a new phase of investigation begins. A scientific revolution, therefore, is nothing more than a transition to a new paradigm, since the decision to reject one paradigm is simultaneously the decision to embrace another. Or, to state Kuhn's thesis in his own words, scientific revolutions are "noncumulative developmental episodes in which an older paradigm is replaced in whole or in part by an incompatible new one."[12]

But the thesis, so stated, has further implications. For one thing, Kuhn claims that, after a revolution has occurred, scientists see a different world. Their new way of conceptualizing nature and its problems is very much like a switch of visual Gestalt. Sense experience is thus not fixed and neutral with regard to different interpretations that may be put upon it. After a revolution the data themselves have changed. And the new ways of looking at things are not closer approximations to the way things are, nor are they closer approximations to the truth. Science seems to progress toward truth, Kuhn admits, but this progress is documented only in periods of normal science, when puzzle solving is going on under the aegis of the accepted paradigm.

Science progresses in such cases for a simple reason: because its progressive procedures are circularly defined as scientific. Thus scientific progress lies in the eyes of its beholders—those engaged in the process, scientists themselves. They progress because they so define their puzzle-solving activity that progress is inevitable. Moreover, their education insulates them from the intellectual world at large. Their textbooks disguise the revolutions that have previously taken place in their discipline, and their authoritative sources make the history of science appear linear and cumulative. Actually the choices by which the scientific community selects new paradigms are made on hunches, on subjective and aesthetic considerations, and have little or nothing to do with objectivity and truth.

Popperian Reaction. The resulting indictment of modern science is devastating in the extreme, and its full implication can be appreciated only when Kuhn's line of reasoning is extended to every other intellectual enterprise, philosophy not excluded. His attack on the concept of

12. *The Structure of Scientific Revolutions*, Chicago and London: The University of Chicago Press, 1962, p. 91; 2d ed., 1970, p. 92.

truth provoked a reaction from Karl Popper and some of his associates in England, most notably Imre Lakatos.[13] The latter, while sympathetic to certain aspects of Kuhn's thesis, felt that Kuhn fails to take account of the results of rational inquiry in furthering human knowledge. Popper himself, as already noted, focused on the method of falsification and saw this as a way of approaching truth, at least as an ideal. He, however, disagreed with the logical positivist and neoempiricist lines of thought as these had developed in the U.S. Meanwhile, Paul K. Feyerabend had attacked the received view of scientific theories and its distinction between observational and theoretical terms as inadequate accounts of scientific practice. Also, he questioned the way in which theory replacement was used to account for advances in science, and in this way he agreed with Kuhn's repudiation of the "cumulative growth of knowledge" view of the scientific enterprise.

Lakatos's critique of Kuhn was more thoroughgoing. His focus was on Kuhn's use of paradigms, which he identified as "super theories" or general theories that exercise a regulative influence on the evolution of science. Lakatos attributed to such theories, which he called research programs, some of the characteristics found in Kuhn's paradigms, but he rejected others that for him made Kuhn's proposal border on the irrational. The crucial difference between the two is that Lakatos believed that scientific progress is not illusory, that it actually comes about, and that it is reflected in ever-more responsible and better corroborated accounts of the cosmos. So he asserted that successive theories within a research program register progress and they do so to the degree that they possess a greater empirical content or have better empirical corroboration. These are the features that make one theory superior to, or more progressive than, another. Therefore the adoption of theories is not a whimsical matter, something based on the social and psychological factors influencing the investigator, but is rather a matter of rational choice based on testable consequences.

Lakatos did not make extreme truth claims for scientific theories, but he implicitly followed the correspondence theory of truth advocated by his associate, Karl Popper. Fundamental to Popper's logic of falsification is the recognition that one theory has more empirical content than another if it has more testable consequences. The more such consequences, the more readily a theory can be falsified, for each testable consequence leaves it open to disconfirmation and ultimate rejection. Any

13. Imre Lakatos and Alan Musgrave, eds., *Criticism and the Growth of Knowledge*, Cambridge: Cambridge University Press, 1970.

theory that is more falsifiable, therefore, and despite empirical test has not yet been falsified, has a greater claim to verisimilitude than a competitor that has not met such a test.

As Popper saw it, the fact that our conjectures and theories can clash with, and be falsified by, something beyond themselves, points to the existence of an independent reality. Moreover, the fact that this reality can have at least a falsifying (and thus controlling) influence on the way we formulate theories means that such an independent reality contributes over the long run to our scientific knowledge. The only reason scientists perform experiments, Popper argued, or why they attempt to verify the predictions of theories, is because they suppose that there is a valid standard of judgment beyond the theory itself. This standard is what he called reality, and statements that correspond to it are what he called truth. In the interest of recognizing progress, therefore, Popper was explicit that "we simply cannot do without something like this idea of better or worse approximation to truth."[14]

The controversy that developed between Kuhn and the Popperians set the philosophy of science movement on rather a new course. Logical difficulties continued to be explored, but they no longer took center stage in the discipline. The history of science obviously came to be taken more seriously, not merely to supply an example or two of how a logical method actually worked, but to be understood on its own terms and in light of the actual context in which science developed. This meant a renewed interest in philosophies other than logical empiricism, and the exploration of social, cultural, and political factors that were instrumental in science's growth. These latter concerns soon broke off from the field and began to constitute a separate discipline in its own right, called the social studies of science or studies in science, technology, and society. But the philosophical core of the philosophy of science continued to reassert itself, and by the 1990s questions relating to epistemology and ontology were again attracting major interest, on a par with that previously given to logic.

6.6 Science and Natural Philosophy

Although occasionally the term "nature" might intrude itself into philosophy of science literature, as in the title of Schlick's *The Philosophy of Nature*, where it is used to designate physical reality in general,

14. *Conjectures and Refutations: The Growth of Scientific Knowledge*, 2d ed., New York: Harper and Row, 1965, p. 232.

surprisingly little interest has been manifested in that concept within the discipline. The same could be said for natural philosophy, possibly for the reason earlier mentioned, namely, that Immanuel Kant's theory of knowledge, by ruling out knowledge of natures or of "things-in-themselves," seemingly had rendered that area of investigation superfluous. Yet the major contributions of the Scientific Revolution—say, those of Gilbert and Harvey, Galileo and Newton—had been made within the context of natural philosophy, long before Kant erected his many-storied edifice. And historians of science, by systematically filling in the gaps that had previously existed between Greek science and that of the early modern period, had provided much information that could link the founders of modern science with their intellectual forebears. But philosophers are slow to change, and philosophers of science are no exception. Apart from Alfred North Whitehead, whose philosophy of organism was actually a philosophy of nature, natural philosophy and its history received scant attention from those interested in the philosophy of science in both the "logical" and "historical" phases just surveyed.

The major exception is philosophers associated with Thomism, who, because of the close link between Aristotle and Thomas Aquinas (from whom Thomism gets its name), have continued to develop natural philosophy as an autonomous discipline and to explore its relationships with modern science. The principal thinkers in this area have been French, Jacques Maritain and Yves Simon, both of whom have taught in the U.S. and whose thought will occupy us in this section. However, since earlier we mentioned the Jesuit university in Rome, formerly the Collegio Romano but now the Gregorian University, we preface our treatment with a brief overview of the Jesuit tradition in natural philosophy, or cosmology, as the discipline there is more frequently called. From the inception of their university in 1551 to the present day the Jesuits in Rome have maintained strong links to Aristotle and Aquinas. Within the Jesuit order there has also been a keen interest in modern science, most manifest in their work at the nearby Vatican Observatory, also under Jesuit charge.

Jesuit Tradition. Much of the stimulus for interest in the philosophy of science at the Gregorian University derives from the writings of a Dutch Jesuit who taught there, Peter Hoenen, the first edition of whose *Cosmologia* appeared in 1931 and the fifth in 1956. His thought has been taken up and developed by the Italian Jesuit Filippo Selvaggi, who has published systematic works on the philosophy of science and whose writings are thus directly pertinent to our interests.[15]

Selvaggi's thesis is that the philosophy of science is identical with epistemology, which he regards as a special part of gnoseology, the discipline that deals with knowledge (Gr. *gnōsis*). Gnoseology treats of knowledge in general, whereas epistemology is concerned with the critique of scientific knowledge (Gr. *epistēmē*), much in the way that critique of science was viewed by Poincaré and Duhem. Selvaggi refines this view by noting that science constitutes the object of epistemology in its formal part, insofar as science is a cognitive process, but not in its material part, that is, in the content of its affirmations about material reality. This latter part can also be the object of philosophical consideration, and then it pertains not to epistemology but to the philosophy of nature. Thus questions relating to atomism, mechanism, causality, space and time, the continuous and the discontinuous, etc., can be examined either by the scientist or by the philosopher. They are not directly within the province of the epistemologist, who can study such problems only indirectly, that is, when judging the formal validity of statements made by the scientist or natural philosopher.

Selvaggi further explains that the philosophy of science has two major divisions: a general part that studies the logical structures and the methods common to all of the sciences, and a special part that analyzes the methods proper to individual sciences or groups of sciences, e.g., mathematical, physical, biological, and human. The general part proceeds from an abstract consideration of the human mind to an analysis of the mind's general cognitive processes and the ways these enter into scientific methods. The special part then proceeds in the light of these principles to a detailed analysis of scientific methodology, to ascertain what facts have been established in the gradual evolution of science, to explain their theoretical justification, and to ascertain the limits of scientific knowledge. This special part, for Selvaggi, is the most difficult but also the most important part of the discipline.

The relationships that should obtain between the philosophy of science and the philosophy of nature are also sketched by Selvaggi. The

15. Selvaggi's titles include *Filosofia delle Scienze*, Rome: Civiltà Cattolica, 1953, *Orientamenti della Fisica*, Rome: Editore Università Gregoriana, 1961, *Scienza e Metodologia*, Rome: Editore Università Gregoriana, 1962, and *Causalità e Indeterminismo*, Rome: Editore Università Gregoriana, 1964. The summary that follows is taken from the first of these works.

philosophy of science, he would maintain, considers science formally as it is the work of the intellect, that is, as it is rational knowledge concerned with physical entities. On this account it overlaps with both logic and theory of knowledge, his gnoseology. The philosophy of nature, as opposed to this, does not consider science itself formally as a work of reason, but rather the objects of its consideration. The latter he enumerates as quantity and natural bodies, space and time, physical and chemical forces, electrons, protons, photons, atoms, molecules, and so forth—implicitly attributing a real or mind-independent status to all these entities. He concludes on the note that, though different from each other, the philosophy of science and the philosophy of nature are intimately related and mutually complementary.

Maritain's Thomism. The Thomist philosopher most often quoted in the U.S. on topics relating to the philosophy of science is Jacques Maritain, a Parisian who studied at the Sorbonne and was inspired by the thought of Henri Bergson before becoming acquainted with that of Aquinas. Maritain has not written explicitly on the philosophy of science as such, but he has discussed extensively the relationships that should obtain between traditional natural philosophy and modern science. His writings have been analyzed by his disciple and colleague Yves Simon, to extract from them materials with which Simon reconstructs what he refers to as Maritain's philosophy of science.[16]

The most distinctive aspect of Maritain's analysis of the philosophy-science relationship is his rejection of a doctrine that originated with Christian Wolff, the eighteenth-century predecessor of Immanuel Kant who made natural philosophy or cosmology a part of metaphysics. Maritain's reading in Aquinas had convinced him that the philosophy of nature was an autonomous discipline distinct from metaphysics, and that its concepts should be situated at the first degree of abstraction rather than at the third, which is proper to metaphysics (see Sec. 4.6). Like earlier Thomists, Maritain also locates modern science, i.e., science as it has developed since the seventeenth century, within the first degree of abstraction. Impressed by the different methodologies and conclusions of the natural philosopher and the modern scientist, however, Maritain employs various distinctions to effect a separation between them, while locating the concepts of both within the first degree of abstraction.

According to one of his formulations, all perceptions of material re-

16. Yves Simon, "Maritain's Philosophy of Science," *The Thomist* 5 (1943), pp. 85–102.

ality have a dual or bipolar character in that they refer to intelligible objects that are apprehended through a complex of sensible properties, themselves stabilized by a center of intelligibility. Such a bipolar representation of physical objects is congruent with the Aristotelian definition of physics or natural science as the science of changeable or sensible being (*ens mobile seu sensibile*). The physical object is itself both intelligible (*ens*) and observable (*mobile seu sensibile*). Neither of these aspects can be neglected if the possibility of a science of nature is to be maintained. Leaving out the observable aspect (*mobile seu sensibile*) means that one is no longer dealing with the physical world, whereas leaving out the intelligible aspect (*ens*) means that one is no longer dealing with conceptual or scientific knowledge. Furthermore, the presence of these two aspects allows for a difference in emphasis on the part of the knower. If the emphasis is put on *ens*, the form of knowledge that results is both ontological and physical and its concerns are those of the philosophy of nature. If the emphasis is put on *mobile seu sensibile*, the form of knowledge that results is physical and empiriological and its concerns are those of the positive sciences. The philosopher of nature is not a metaphysician and his definitions must include reference to sensible matter, the data of sense experience. The empirical scientist is not a mere collector of data and the regularities he observes must be organized under some intelligible formality, what Maritain refers to as a *ratio entis*.

In an alternate way of formulating these two aspects of natural knowledge, Maritain argues for a difference between ontological or dianoetic knowledge of nature, which he says is characteristic of the philosophy of nature, and empiriological or perinoetic knowledge, which he finds typical of modern science. Ontological knowledge, in this understanding, penetrates through sensible appearances to attain to knowledge of essence (and therefore is called *dia*-noetic), whereas empiriological knowledge never goes beyond the phenomena but remains always circumferential (and therefore is *peri*-noetic). Given this distinction, Maritain feels he can preserve the possibility of valid philosophical knowledge of natures or essences, a possibility denied by Kant and his followers, and at the same time acknowledge the positive character of modern science as this has been maintained by Comte, Duhem, and the empiricist tradition.

Granted Maritain's point about the dual character of natural knowledge, it would seem that the philosophy of science occupies a somewhat ambiguous position between the philosophy of nature and the positive sciences. Simon recognizes this and attempts to situate its literature, which, he says, stands on the border between natural philosophy and modern science, in the following way. When a philosopher interested in science or a scientist interested in philosophy considers problems arising in modern science, both the natural and the empirical points of view may appear in his exposition. Any confusion between the two can then be removed by analyzing a few key concepts. According as the analysis goes up or down, that is, according as the concepts require explanation either in ontological terms or in terms that refer more and more to empirical aspects, one will be able to discern whether the treatment is philosophical or scientific in its orientation. In Simon's view, therefore, the philosophy of science functions at the first degree of abstraction and tends by its nature toward either polarity, that of natural philosophy or that of positive science, depending on the type of analysis in which the philosopher of science engages.

A difficulty that arises in both of Maritain's accounts of the type of knowledge attained in modern science is his tacit acceptance of the positivist view of science, which effectively rules out the possibility of the scientist's (as opposed to the philosopher's) attaining any certain and causal knowledge, that is, ontological knowledge, of the real world. Taken literally, therefore, his view of the relationship between science and philosophy seems on this account to be little different from Duhem's. Simon was aware of this problem and approached it in the following way.

What Maritain calls the intelligible aspect or *ratio entis* of empirical science, Simon explains, can take either of two forms. One is the somewhat confused grasp of an ontological subject around which various phenomena can be organized, as in sciences that are heavily classificatory, such as geology, biology, archeology, etc.—what Maritain calls empirioschematic sciences. The other is the explicit grasp of quantifiable aspects of the real world, as in sciences that make extensive use of mathematical reasoning—what Maritain calls empiriometric sciences. It is when discussing the second group of sciences that Simon makes specific reference to Duhem. Simon notes that the very nature of mathematical abstraction is such that its concepts can be indifferent to the reality of its objects. As a consequence mathematical physics, under the attraction of mathematical form, tends not to differentiate between a mind-independent being (an *ens reale*) and a mind-dependent being (an *ens rationis*). Should this tendency remain unrestrained, one could say that physical theories do not explain phenomena in terms of their real causes and so fail to give an ontological account of physical events. This is the conception of physics, says Simon, that was upheld by Pierre

Duhem. But for Maritain, he observes, this interpretation is an oversimplification. In actual practice the attraction exerted on physics from mathematical form is not unrestrained. Though the form is mathematical, the matter is physical, and the attraction of the latter counteracts that of the former, impelling the mathematical physicist to focus on the real and seek explanations in terms of physical causes.[17]

6.7 Science and Nature

Simon's reconstruction of Maritain's philosophy of science appeared in 1943, at a time when the discipline was still much under positivist influences. Fifty years later the intellectual climate has changed and a new consensus has begun to emerge among philosophers of science.[18] This is neither that of the "logical" phase nor that of the "historical" phase, but rather one that reaps the fruits and benefits of both. The emerging consensus gives indication that the study of science has brought the movement closer, at least, to the study of nature, and thus opens the possibility that the philosophy of science may be more intimately related to the philosophy of nature than has hitherto been thought. The new climate of opinion therefore allows breathing room for investigating the

17. Reasons of space prevent me from treating here the views of a Belgian Thomist, Charles De Koninck, who taught for many years at Laval University in Canada and who was an outspoken critic of Maritain's Thomism as well as Reichenbach's "scientific philosophy." De Koninck's main criticism of the frontier Maritain would erect between natural philosophy and modern science is that people do not cease to be philosophers of nature when they continue to ask more and more specific questions about the reality they are studying. He saw Reichenbach, on the other hand, as simply bypassing any consideration of the generalities of which one can be certain and which must be known at the outset if one is ever to attain detailed knowledge of nature. Thus De Koninck opposed any divorce of philosophy of science from philosophy of nature, on the ground that this would isolate specialized knowledge from general knowledge and render the former totally unintelligible—that is, as lacking contact with, and relevance to, what it proposes to explain in ever greater detail. More particulars are given in the author's essay, "Toward a Definition of the Philosophy of Science," *Mélanges à la mémoire de Charles de Koninck*, Quebec: Les Presses de l'Université Laval, 1968, pp. 465–485, reprinted in *From a Realist Point of View*, 2d ed., pp. 1–21.

18. The outlines of this new consensus may be seen in a recent anthology edited by Richard Boyd, Philip Gasper, and J. D. Trout, *The Philosophy of Science*, Cambridge, Mass. and London: The MIT Press, 1991. This, along with a similar work, *Introduction to the Philosophy of Science*, ed. Merrilee H. Salmon et al., Englewood Cliffs, N.J.: Prentice Hall, 1992, provides the basis for much of what follows.

question posed at the beginning of this chapter, namely, whether the philosophy of nature sketched in the first part of this volume can rightfully lay claim to being also a philosophy of science. A full answer to that question, along with the many qualifications it might entail, will require the use of materials to be developed in the remaining chapters of this second part. But a preliminary answer may be sketched with profit at this point, for if nothing else it will serve to map out the terrain that is to be covered in what is to come.

The New Consensus. To be more specific about the new consensus, several of its characteristics are noteworthy in the context of this study. For one, empiricism is no longer the proclaimed epistemology behind the philosophy of science movement and various realist alternatives to it are being actively explored. Prominent among these are what some have referred to as naturalized epistemologies, wherein the concept of "natural kind" is again assuming prominence and causal conceptions of reference are being investigated to replace the standard empiricist accounts.[19] The history of science is being taken even more seriously than it was under Kuhnian inspiration, with the result that the hitherto accepted dichotomy between discovery and justification—which leaves the study of the first to psychology or social studies and claims only the second as the concern of the philosopher (or the logician) of science—is no longer an accepted dogma. And, most important, an overarching logical imperialism that would pretend there is only *one* philosophy of science applicable to all disciplines is giving away to the realization that there can be a legitimate philosophy of physics, of biology, of psychology, and of the social sciences, and that the one is not reducible to the other. In other words, the content or subject or matter being investigated, the content logic that in former times was regarded as "material" logic,

19. Here we make no attempt to canvass the various naturalized epistemologies that have been appearing in recent years, some of which are based on concepts of nature and science very different from those being developed here. A recent example of the latter is Abner Shimony's *Search for a Naturalistic World View*, 2 vols., Cambridge: Cambridge University Press, 1993. Shimony gratuitously adopts the view that man evolved from matter and and sees such an origin as having ruled out his attaining any veridical knowledge of nature and natural forms. In light of the argument advanced above in Sec. 5.9, his reasoning is correct if one accepts his hypothesis of a material origin; otherwise, *quod gratuiter asseritur graduiter negatur.* For a brief overview of Shimony's thought see his "Empirical and Rational Components in Scientific Confirmation," *Proceedings of the 1994 Biennial Meeting of the Philosophy of Science Association*, vol. 2, East Lansing, Mich.: Philosophy of Science Association, 1995, pp. 146–155.

must henceforth be taken to be on a par with "formal" logic. The fact that different natures are being studied in the different special sciences inevitably makes a difference in the way the philosophy of those sciences is to be investigated.

The most fundamental change behind this new consensus is a relinquishing by many philosophers of the doctrines David Hume hitherto imposed on their discipline. The reason for their doing so is clear, namely, the undisputed progress of science in the twentieth century, a progress that invalidates many of Hume's key suppositions. Much as Whewell could criticize Bacon for basing his canons on a primitive and undeveloped science, so the philosopher of the late twentieth century can criticize Hume for imposing strictures on scientific knowledge based on the science of the eighteenth century—in particular, on the then-understanding of the microstructure of matter. Simply put, we ought do for Hume what Galileo proposed to do for Aristotle, as mentioned in the preface to this volume. We should say that if Hume were alive today he would side with the anti-Humeans rather than with those who adamantly defend his outdated teachings.

In both his *Treatise of Human Nature* (1739–1740) and his *An Enquiry concerning Human Understanding* (1748) Hume argued that, in the study of nature, there is no way one can either discover or demonstrate any necessary connection between cause and effect on the basis of *a priori* reasoning. He saw that such a connection would have to be founded on observable experience, and thus, by implication, on the basis of *a posteriori* reasoning. Up to this point he was on solid ground, but from then on his theory of knowledge failed him. Hume could not see how ordinary sensory qualities could ever disclose any power or energy within the natures of things that could effect the appearances they present to us. Man's natural state of ignorance was such, he thought, that natural powers have to remain "secret powers," and, as a consequence, that the natures underlying them have to remain secret too. Unfortunately this line of reasoning also appealed to Kant, despite the fact that it involves a very superficial way of viewing the properties of natural objects—"superficial" in the primitive sense of *superficies*, the Latin term for surface. A surface viewing of any nature, whether it be inorganic, plant, or animal, is almost the polar opposite of a scientific study of that nature, as the subsequent history of science has shown. This is the whole point of the materials that have been presented in the first part of this volume. Hume, penning away in his library, can be excused for not knowing or even suspecting what "secrets" the human mind would unveil in centuries to come, and Kant likewise, when writing his famous *Critique* *of Pure Reason* (1781). But that excuse does not suffice for twentieth-century philosophers, particularly those who present themselves as versed in modern science and its discoveries.[20]

Logic and Science. A realist and up-to-date view of the philosophy of science, as opposed to a Humean or Kantian view, brings it very close to a philosophy of nature, so much so that philosophy of science can be seen, with proper qualifications, as itself a part of the philosophy of nature. To explain this it will be necessary to resume discussion of the traditional concept of science touched on in the preceding chapter and how this concept may be related to logic, which there was listed among the liberal arts (Sec. 5.3). In earlier discussions of types of concepts (Sec. 4.6) and of truth (Sec. 4.9), implicit reference was made to the distinction between formal logic and material or content logic, but no mention was made of a problem that has been much debated within Aristotelianism, namely, whether logic, in addition to being an art, may also be considered a science. Allied to this problem is another topic not yet mentioned, the difference between logic as an art that can be taught (*logica docens*, logic "teaching") and logic as it is used (*logica utens*, logic "using"), the latter particularly in the development of the natural and human sciences.

Beginning with this last distinction, when taught as a discipline in its own right logic (*logica docens*) stays exclusively in the domain of logical being or of second intentions (Sec. 4.6–7). One may say that this is pure logic, and as such is to be differentiated from logic that is applied to things or put to use in the study of nature (*logica utens*). The possibility of this second kind of logic, applied logic, raises interesting questions. When one is applying logic to physics, for example, is the person doing so functioning precisely as a logician or as a physicist? If the former, and especially if the person reasons to conclusions that are strictly scientific, that is, cannot be otherwise, then it would seem that logic is not merely an art but also a science. On the other hand, does the fact that physicists may reason logically entitle one to say that, when doing so, they are functioning no longer as physicists but as logicians? Would such an inference not entail that physics itself is not a science in the strict sense, that logic alone is the science that enables one to draw necessary conclusions?

20. See R. H. Schlagel, "Meeting Hume's Skeptical Challenge," *Review of Metaphysics* 45.4 (1992), pp. 691–711. See also Schlagel's "A Reasonable Reply to Hume's Scepticism," *British Journal for the Philosophy of Science* 35 (1984), pp. 350–374.

These questions are difficult to answer, but a common response is the following. The subject matter in which any demonstrations are being arrived at is what ultimately determines the discipline to which the demonstrations should be ascribed. Therefore, if conclusions are being reached with regard to logical being as such, they pertain to logic and the person reaching them is functioning as a logician. If, on the other hand, they are being reached with regard to physical entities, they pertain to physics and the person reaching them is functioning as a physicist. On this account, an applied demonstrative logic, say, one that reaches certain conclusions in physics, is not logic at all. It is actually the science to whose subject matter logic is being applied, in this case physics.

This conclusion is suggestive of a similar question relating to the philosopher of physics as related to the physicist, when the philosophy of science is conceived as the logic of science. Is the logic of physics really any different from physics itself? Or, extending the question somewhat, is the logic of science really any different from science itself? How one answers these questions depends very much on what one means by logic and by science. Within the Aristotelian tradition, science is understood in the sense of *scientia*, that is, certain knowledge through causes and effects, where a necessary connection can be discerned between the two. Here, if by logic one means material logic, and particularly the demonstrative logic treated in the *Posterior Analytics*, both questions would be answered in the negative. (Within the Humean tradition, on the other hand, since the human mind is powerless to discern necessary connections in nature, both answers could well be affirmative, since most philosophers or logicians of science seem to think that, in their discipline, they are doing something different from science.)

The ground for the Aristotelian reply invokes the distinction between *logica docens* and *logica utens* explained above. In the *Posterior Analytics* Aristotle worked out in rigorous fashion all the requirements for strict scientific knowledge. (These are examined in detail in Chap. 8 below.) Those who are expert in reasoning about those requirements, who understand the meaning of cause and effect, definition and demonstration, etc., can properly be called "logicians." They may not be "scientists," in Aristotle's sense, but that is not the point at issue. The crucial point is that as logicians they are doing *logica docens*, whether they are engaged in teaching logic or not. Those, on the other hand, who are studying a particular subject matter and are using the canons of the *Posterior Analytics* to investigate it, have left the realm of *logica docens* and have shifted over to *logica utens*. Here the position is more nuanced. If they succeed in demonstrating in that subject matter, they have then attained scientific knowledge of it and have become "scientists" in the stricter sense. They are not "logicians" except in the sense that they know a logical treatise; what has happened is that their successful use of the teaching contained in that treatise, their *logica utens*, has made each into, say, a mathematician, or, to use the modern equivalents of the natural philosopher of Aristotle's day, a physicist, an astronomer, a chemist, etc. If, on the other hand, they do not succeed in attaining demonstrative knowledge but have only opinions about the subject matter they are investigating, they are in a sort of no man's land between logic and the real sciences. Actually they are dialecticians and, in the Aristotelian view, have to employ the canons of the *Topics* until they can extricate themselves from probable reasoning and make claims for truth and certitude.[21] Only when they can do this do they truly "know," in the sense of having scientific knowledge of their subject matter.

If the Aristotelian ideal of *scientia* or demonstrative knowledge is achieved, on the other hand, it would seem to follow that the question posed at the outset of this chapter—whether a philosophy of nature as explained in the first part of this volume may also be termed a philosophy of science—can be answered in the affirmative. What the philosopher of science would then be doing is science itself, and if the science is natural science, then the philosopher of science is no different from a natural philosopher or a natural scientist.

6.8 The Philosophy of Science

How, then, should one define the philosophy of science? Posing the question on the modern scene requires that one set aside the foregoing discussion for the moment and consider the present state of the discipline as it is viewed by most of its practitioners. On this accounting the "received view" would be heavily problem oriented: the philosophy of science is a discipline concerned with philosophical problems raised by modern science. The main problems should be clear from the foregoing survey: the meaning and interpretation of facts, laws, and theories; the logical structure of science; and the methodology it generally employs. The very expression itself, "philosophy *of* science," further presupposes at least a minimal bifurcation between philosophy and science. Implicit in it is the idea that philosophy in some way antedates science and is thus

21. The terms "dialectics" and "dialectician" take on various meanings in different philosophical systems, say, in Platonism, Aristotelianism, Kantianism, Hegelianism, and Marxism. Here we obviously intend the Aristotelian sense, as detailed below in Sec. 7.8.

available for its critique and evaluation. That helps to define science, for what is obviously meant by that term is "modern science." The qualification "modern" would seem to alter the signification of the word "science" so that it no longer means the same as the terms from which it derives, the Lat. *scientia* and the Gr. *epistēmē*.

The Modern Scene. Some of the characteristics of this "modern science" may now be enumerated. Obviously it is different from "Greek science," "medieval science," and "Renaissance or early modern science," all of which seem to have made stronger knowledge claims than does recent science. One may ask whether twentieth-century science is also different on this account from eighteenth- or nineteenth-century science, for present-day scientists now seem less sure of their science than were their predecessors of the preceding two centuries. On the current view, "science" is no longer certain and unrevisable knowledge. Despite being organized and systematic knowledge, it is fallible, ever subject to revision, and always characterized as "probable" in varying degrees. By and large the content is empirical, experimental, and mathematical in orientation—what Maritain called empirioschematic or empiriometric knowledge. The favored methodology is conditional or hypothetical reasoning that is "verified" or "falsified" by empirical findings. To the extent that it employs mathematical forms of reasoning it has elements in common with applied mathematics or what was earlier known as "mixed mathematics," "mixed sciences," or "middle sciences," regarded by many as its historical antecedents.

The "philosophy" that has been embodied in the philosophy of science movement up to now, from the foregoing account, is clearly empiricism of the Humean variety.[22] This is the problem being addressed by the new consensus. Empiricism is itself a skeptical philosophy that derives from the empirical shortcomings of eighteenth-century science, and so some circularity is discernible within the philosophy of science movement itself. It uses an earlier and less-informed stage of science as the foundation for a philosophy that would critique a later and presumably better-informed stage of the same enterprise. Reichenbach's proposal to discard all previous philosophy for a "scientific philosophy," that is, a philosophy explicitly based on the findings of science, would exacerbate this situation even further. A philosophy of science that is nothing more than a "scientific philosophy of science" is both circular

22. Craig Dilworth, "Empiricism vs. Realism: High Points in the Debate During the Past 150 Years," *Studies in the History and Philosophy of Science* 21.3 (1990), pp. 431–462.

and redundant. The concept of "philosophy" that underlies the movement is therefore deficient, and a broader and more inclusive definition of philosophy would seem to be a clear desideratum. In such circumstances, a return to the premodern view of philosophy may be welcome for what it might contribute to a revised definition of the philosophy of science, presumably until something better comes along.

An Aristotelian View. The traditional understanding of philosophy, basically Aristotelian, is closely allied with that of *scientia* or *epistēmē*, that is, certain or unqualified knowing that is grasped by the human mind either directly, because evident, or, if not, through causal analysis and demonstration. Philosophy itself, in this view, is not a single discipline but rather an aggregate of several disciplines and so cannot be defined strictly. The disciplines that make it up are all sciences in the Aristotelian sense, and they are concerned either with beings of reason, mind-dependent beings, which are studied in logic, or with real being, mind-independent being, which forms the subject of study for the rest. The latter consider real being either speculatively or practically, speculatively, in order to understand, practically, in order to act. Among the speculative disciplines are commonly listed natural philosophy, concerned with sensible matter, mathematics, concerned with quantified being, and metaphysics, concerned with being as such, i.e., as separable from matter and not restricted in any way. The practical disciplines then include ethics, which considers how an individual human being should act to achieve happiness, that is, his or her perfect fulfillment as human, and politics, which considers how humans should act together to achieve their joint perfection in society and in the body politic. All of these disciplines then have further subdivisions, some of which have already been indicated in the exposition to this point.

Within the Aristotelian scheme, epistemology is not a separate discipline distinct from all the others, since it falls to each of the disciplines listed above to justify its own knowledge claims as it develops. To the extent that it can be treated systematically, however, it is usually assigned to metaphysics or to logic. It is relevant to metaphysics because the latter has the broadest scope of all the disciplines—all of being, real and rational, to which humans have unlimited access through their power of intellect. It is relevant to logic because it falls to that discipline to lay down norms for the acquisition of *epistēmē* in any subject matter. Such norms are treated in the *Posterior Analytics*, which, being concerned with *epistēmē*, is what gives epistemology its name.

Thus understood, how does philosophy stand in relation to modern science? It would seem undisputed that some knowledge of philosophy is already implicit in the scientific enterprise. One must be logical in thought processes in order to be a scientist. And, anterior to any speculative doubts that arise within a particular field of study, one must be an epistemological realist, seeking truth about nature or the domain of nature that serves to define the field of interest. And yet the philosophy of science would not be identified with either logic or epistemology. Although it makes extensive use of logic, and particularly formal logic, it is not concerned with beings of reason as such. Its ultimate objective would seem to be knowledge of nature, not knowledge of mind-dependent being in its various articulations. Nor is philosophy of science epistemology pure and simple. Despite its being concerned with epistemological problems, it is not concerned with the validation of knowledge as such, but only with the validation of knowledge within a particular field of inquiry, just as are all other disciplines.

Two other broad areas may also be excluded from consideration. Philosophy of science is not metaphysics in the Aristotelian sense. It is not concerned with being as separable from matter, but rather with natural being that has sensible matter as one of its components. Ontological questions, like epistemological questions, arise in literature on the philosophy of science, and, if metaphysics is understood to be the study of any reality that transcends sense experience, these questions may be referred to as "metaphysical." But that is an improper use of the term "metaphysical," from the point of view here being exposed. Similarly, philosophy of science does not pertain to politics or to the social and political sciences allied to that discipline, although "social constructivists" interpret much of modern science in this way.

By a process of elimination, therefore, we come to natural philosophy and mathematics as the parts of traditional philosophy that are most relevant for defining the philosophy of science. Since the central interest here is not the philosophy of mathematics, which presents its own special problems, we may set aside pure mathematics, while allowing that mixed mathematics has important bearing on some parts of science in its modern understanding. That leaves natural philosophy or natural science as the part of traditional philosophy to which the philosophy of science is most germane—precisely the conclusion arrived at in the previous section, though by a different line of reasoning.[23]

23. This conclusion has also been adumbrated in the author's essay on Charles De Koninck cited in note 17 above.

Philosophy of Science. Obviously that conclusion now requires further articulation, which we propose in the following thesis. Philosophy of science is a specialization or subdiscipline within the philosophy of nature that has been occasioned by the growth of modern science with its characteristic methodology. Generalities about nature, its principles and its properties, and basic concepts such as matter, form, motion, the infinite, space, time, the continuum, etc., are treated in the philosophy of nature as such, the prototype for which is Aristotle's *Physics*. In addition to general studies, however, nature can be studied in specific detail, using the methods that have come to be characteristic of the natural sciences. These methods frequently involve logical and mathematical constructions from which valid physical knowledge can be disengaged, either by demonstration, by falsification, or by probabilistic reasoning. The essential task of the philosopher of science is to assist in the task of disengaging valid physical knowledge from the logical and mathematical scaffolding in which it may be imbedded. This task is actually performed by the scientist, as opposed to the philosopher of science, in most instances. Yet, in the more difficult cases, there is a role for the philosopher of science, who may bring to the scientist's explicit awareness the presuppositions and constructions wherewith the puzzling and enigmatic results are being obtained.

So understood, modern science and the philosophy of science are not essentially different disciplines. The scientist is doing in practice what the philosopher of science is doing in a more reflective way. A person who speaks or writes good English simply puts into practice what the grammarian proposes theoretically and systematically. This is similar to the ancient distinction between doing something *in actu exercito*, in an exercised or implied way, and in doing it *in actu signato*, in a signed or explicit way. One could say, therefore, that the scientist does only *in actu exercito* what the philosopher of science does *in actu signato*. Just as the grammarian can be of help to the speaker or writer who gets tangled up in complicated expressions, so the philosopher of science can assist the scientist who gets entangled in a complex reasoning process about nature and thus has doubts about the meaning of his discoveries. And since many difficulties and complexities are peculiar to the subdisciplines that make up modern science, this allows room for specializations within the philosophy of science also. Thus, one can have a philosophy of physics, or biology, of psychology, of the social sciences, and so on, corresponding to the various subdisciplines that now exist within modern science.

To go a step further and rejoin the discussion of the preceding section, modern science is also not essentially different from the philosophy of nature (as opposed to the philosophy of science). Here the problem hinges on what constitutes valid knowledge of nature, and whether such knowledge is certain or merely probable. If modern scientists are not certain of their results, if they are always immersed in the logic of discovery, one would hesitate to say that they have arrived at valid knowledge of nature. If, on the other hand, they have been able to identify the true causes of a particular phenomenon, and are able to demonstrate its various properties in terms of them, then their results constitute *epistēmē* and pertain as much to natural philosophy as to modern science. The point to be made here is that modern scientists, in view of their empirical and mathematical techniques, are not to be excluded from the ambit of those who can achieve demonstrative knowledge. They do not have to become "philosophers" in some honorific sense in order to do so, as though philosophers alone are capable of providing true demonstrations. To the degree that it is able to demonstrate conclusions, modern science is just as philosophical as Greek, medieval, or Renaissance science. It too will follow the norms of the *Posterior Analytics*, but, as has been argued in the preceding section, the logic involved is *logica utens*. As such it is no longer logic pure and simple but rather the discipline to which the logic has been applied, in this case natural philosophy.

This characterization of the philosophy of science includes all of the elements that have been ascribed to the philosophy of science earlier in this chapter, from the pioneering work of William Whewell down to the new consensus. What remains to be done is to flesh out the definition that has been proposed, first, by analyzing in fuller detail why modern science is mostly concerned with probable argument and on that account is regarded as always fallible and revisable, and second, by showing that to characterize science as inevitably fallible is an overly pessimistic evaluation, since it is capable of arriving at certain knowledge, at least in some instances, once its techniques of demonstration are correctly understood. The first development is sketched in the following chapter, entitled "Science as Probable Reasoning," and the second in Chap. 8, entitled "The Epistemic Dimension of Science," along with the two chapters that follow.

7 Science as Probable Reasoning

Of the tasks set out at the end of the previous chapter, the easiest is that of explaining the dialectical character of modern science, that is, why it typically is not able to achieve demonstrative or apodictic knowledge but must settle for conclusions to which assent is given only with greater or less probability. This aspect of science has been fully explored within the logical empiricist tradition, and thus a recapitulation of some of the findings of that tradition will provide the essential elements on which the probabilist view rests.

As its name suggests, logical empiricism makes heavy use of logic in its analysis of scientific experience. The logic that it employs, as explained in our discussion of the logical construction of science (Sec. 6.4), is a particular type of formal logic known as mathematical logic or symbolic logic. The basic logical forms in this logic are those of the proposition, on which account it is called propositional logic. In this logic, a proposition is represented by a symbol such as *p* or *q* and then treated as units that can be regarded as true or false without regard for its content or inner structure. A major concern in the development of this logic is that of analyzing the relationships that can obtain between propositions. Two such relationships have already been mentioned in Sec. 4.6, namely "and," as in "*p* and *q*," the relationship called conjunction, and "if . . . then . . . ," as in "if *p* then *q*," the relationship called implication. The combination of these two relationships yields argument forms that are pervasive in modern science, such as, for example, the hypothetical-deductive form already mentioned: "If *p* then *q*, and *q*, therefore *p*."

To appreciate the strengths of this type of formal logic, but also to become aware of its limitations, it will be necessary to introduce later in this chapter some elements of a logic of terms or a logic of concepts. In light of the development in Part I of this volume, the term "a logic of concepts" is to be preferred over "a logic of terms." Terms are signs of concepts, and concepts permit an easy transition into a material logic, or a content logic, such as is developed in Aristotle's *Posterior Analytics* and his *Topics*. A material logic is more adaptable than a formal logic for treating problems relating to probability and necessity as these occur in the sciences, since scientific judgments have to be made on the basis of the matter or content and not merely on the basis of the form of the argument. In this chapter, therefore, materials will be introduced that are useful for understanding not only probable reasoning but also necessary reasoning as this is to be explained in the following chapter.

In our exposition of concepts in the earlier context (Chap. 4), we differentiated between real concepts (those that have existence in the mind and, in some way, outside the mind as well) and logical concepts (those that have existence in the mind alone). Among real concepts we differentiated between physical, mathematical, and metaphysical concepts on the basis of their degree of abstraction from the sensible matter perceived in ordinary experience. Both everyday language and the discourse of the natural sciences, we maintained, normally make use of physical concepts. Occasionally people employ grammatical concepts such as "subject" and "predicate," and then they get involved in the type of discourse we have characterized as logical. But now to be discussed is a special type of physical concept, not yet treated, which seems to be especially characteristic of modern science and which we shall call scientific concepts. These arise from science's heavy emphasis on experimentation and measurement and its concern with theories that serve to explain their results. For purposes of convenience we shall divide such scientific concepts into two types, namely, metrical concepts and theoretical concepts. Both are of special importance: scientists make extensive use of measurements, and for them must employ metrical concepts; they also tend to theorize when explaining the relationships discerned among the measurements, and for such speculation they make use of theoretical concepts. At this point we introduce these new types of concepts in the context of propositional logic; in the next chaper we shall consider them again when exploring their epistemic content.

7.1 Measurement and Metrical Concepts

As the name implies, a metrical concept is one that expresses the result of a measuring process or measurement. Measurement may be defined as the process or technique of correlating numbers with things that are not patently numbered in the order of nature. Alternatively, the term designates the relation that arises from such a process. Measurement is usually effected by comparing observable phenomena with a suitable metric, although sometimes it is the result of a mathematical calculation based on data that are not directly accessible to experience. As employed in the physical sciences, the measuring process is itself an interaction between a measuring instrument and the thing measured, and on this account the objective validity of the measuring process is dependent on corrections, sometimes involving theoretical interpretations, to account for the perturbing effect of the instrument.

From an Aristotelian perspective, measuring is the process by which the quantity of a thing is made known. It is applied directly to physical bodies when their discrete quantity is made known, say, by counting the number of objects in a room, or when their continuous quantity is measured, say, by using a scale to determine individual lengths. In current practice the term "measurement" is sometimes applied to counting, as seen, for example, in the Geiger counter, but more commonly it is reserved for determination of dimensive or continuous quantity.

Quantitative Measurement. The elements involved in direct measurement can be explained in terms of the requirements for a quantitative measurement, say, the determination of length. Such measurement first presupposes a unit: the unit may be one that occurs naturally, such as the foot, or it may be one fixed by convention. The choice of a conventional unit is not completely arbitrary, but is dictated by the unit's suitability as a minimum dimension into which lengths can be divided. Again, the unit must in some way be homogeneous with the thing measured. For example, if length is to be determined, the unit must be a length. Similarly, the thing measured must be uniformly structured and continuous to permit the application of the same unit to each of its parts.

Another requirement is that the unit of measurement and the object being measured must be invariant throughout the measuring process. This ideal is never completely realized for any physical object, since all bodies continually undergo change. Yet a practical invariance is not only detectable but more or less guaranteed by the nature of both the object measured and the standard used. For example, a person's body temperature, although varying over a small range, is held constant by natural causes. Similarly, the unit of time is determined by the rotation of the earth and the gram by the mass of one cubic centimeter of water, both of which are maintained constant through the regularity of nature's operation.

Perhaps the most important requirement is that measurement involves a judgment of comparison between the object measured and the measuring unit. Such a judgment is an intellectual operation, although it presupposes a physical process. The attempt made by some operationalists to reduce every measurement to the manipulation of instruments alone thus overlooks an essential feature of the measuring process. Instruments cannot measure. Ultimately they require mind, which, because of its reflexive character as a self-reading instrument, can effect the judgment of comparison and so make the measurement. These requirements for the direct measurement of quantity or bodily extension are also applicable to spatio-temporal measurements. They can likewise be applied to certain types of quality, but not without adaptations that require further explanation.

As employed in the physical sciences, a measurement cannot be made to an infinite degree of accuracy. There are two reasons why this is so. The first is that all such measurements reduce to a measurement of continuous quantity, and the only way in which number can be assigned to such quantity is in terms of a conventional unit. For infinite accuracy, this unit would have to approach zero as a limiting case. Attaining the limit would itself involve a contradiction in terms, since a number cannot be assigned to a unit of zero, or nonexistent, magnitude. The second limitation arises from specifying the conditions that attend a particular measuring process. Since these involve details that are themselves infinitely variable, they can be specified only approximately. For all practical purposes, however, it is possible to specify the range of magnitudes between which a given measurement is accurate, depending on the unit involved and the circumstances of measurement.

Qualitative Measurement. Physical qualities, because present in quantified bodies and intimately associated with the quantity of such bodies, can themselves be said to be quantified. Their quantity can be measured in two different ways, giving rise to the two measurements that are usually associated with physical quality, namely, extensive and intensive measurement. Physical qualities receive extensive quantification from the extension of the body in which they are present; thus there is a greater amount of heat in a large body than in a small, assuming both to be at the same temperature. They receive intensive quantification, on the other hand, from the degree of intensity of a particular quality in the body. If two bodies are at different temperatures, for example, there is a more intense heat in the body at the higher temperature, or it is the hotter, and this regardless of the size of either.

Measurement of the extensive aspect of physical qualities, being effectively the same as the measurement of length, area, and volume, has the same requirements as those for quantitative measurement. Measurement of the intensive aspect is more difficult and requires techniques that depend on causal interactions between the body possessing the quality and another body. These techniques are basically of two types, one from an effect, that is, the change a quality produces in another body, the other from a cause, that is, the agent that produces the quality's intensity in the body in which it is found. Both provide indirect ways of measuring qualitative intensity through a cause-effect relationship.

If the quality is an active one, that is, if it produces alterations in other bodies, it can be measured by the effect it produces in such a body, thus making the latter a measuring instrument. In this way, heat intensity is measured by a thermometer containing a substance that expands noticeably when contacting a hot object. Similarly, the intensity of sound is measured by vibrations produced in a microphone, and light intensity by electric current generated in a photocell. In each case, the intensity of an active quality in one subject is measured by the quantity of the effect it produces in another. Since the production of this effect alters the intensity of the quality being measured, usually some correction is required to take account of the perturbation.

If a quality is not active and so does not produce discernible effects, its intensity can alternatively be measured through some type of causality required to produce it in the subject body. In this way one measures the intensity of light on an illuminated surface by the number of foot-candles emitted by the source illuminating it. A variation on this technique is that of employing an instrumental cause to measure some modality of the principal cause that actively produces the quality. An example would be using a prism or ruled diffraction grating to selectively refract and measure the wavelength of colored light incident on an opaque surface, and in this way indirectly to measure the ability of the surface to reflect light of a particular color.

Metrical Concepts. To return now to metrical concepts, should one inquire about the size of the lead ball referred to in Sec. 4.6, one could use a calipers to measure its diameter and obtain a result, say, 7.2 centimeters. The meter is a conventional standard, originally the length of a molybdenum bar preserved in Paris under standard conditions of temperature and pressure, but since 1984 defined as the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458th of a second. The measurement "7.2 cm." is what we shall understand as a metrical concept. It contains a number, sometimes further specified by the limits of accuracy to which it has been ascertained, such as "7.2 ± 0.1," plus a unit, in this case the centimeter or hundredth of a meter. Similarly, one might weigh the lead ball to determine its gravity or weight and obtain the result "524 grams" This again is a metrical concept, combining the number 524 with the unit of mass, the gram. Alternatively, to further specify how cold the lead ball might be, one might measure its temperature and get the result "3° C." or "3 degrees Celsius," which again is a metrical concept.

A great advantage of metrical concepts is that they enable us to associate mathematical concepts and operations with physical phenomena and thus make the latter more tractable for purposes of calculation. They also confer greater intelligibility and objectivity on the physical concepts for which they are counterparts. And they do this without being less real than physical concepts, even though they involve a component that is more abstract. If the lead ball is actually 7.2 cm. in diameter, for example, then the "7.2 cm." qualifies as a real concept according to the definition of the real stated above. Again, to make the statement, "The lead ball is 7.2 cm. in diameter," is to make a true statement or to attain the truth, whereas to say in such circumstances "The lead ball is 5.9 cm. in diameter" is to state a falsehood. Thus metrical concepts provide a basis for determining the truth about reality in ways that are essentially no different from the physical concepts discussed in previous chapters.

Another advantage of metrical concepts is that they can serve to extend the domain of the physical into the areas of the very small and the very large. Once a unit has been specified on the basis of sense observation, it is possible to assign a number to it that might correspond to a reality that is not directly perceptible to the senses but is nonetheless measurable. For example, suppose that a monochromatic yellow light ray has been shown to have a wavelength that is very small compared to the meter but can be measured in terms of a unit that is 10^{-10} meter long, or one ten-billionth of a meter, called the Angstrom unit (written Å). By a method of indirect measurement one might determine that the wavelength of this particular light ray is 5745 Å. The unit and the wavelength so measured are certainly invisible, and yet this does not make them unreal or make statements concerning them untrue.

The same could be said about the domain of the very large, such as is treated in astronomy. One might measure a length or distance that is exceedingly great in terms of direct sense experience by using the light-year, that is, the distance light will travel in one year. One cannot see a light-year in the same way one can see a meter stick, and yet one can speak meaningfully and truthfully about distances measured in terms of it, just as one can of lengths measured by the Angstrom unit.

7.2 Theories and Theoretical Concepts

Unlike "measurement," the term "theory" has no precise meaning that is uniformly accepted in various branches of science. It normally connotes a general, systematic account of a subject matter that is at root conjectural or hypothetical. Theories differ from hypotheses mainly in the broadness of their respective concerns: the term "hypothesis" suggests a specific knowledge claim that is as yet unsubstantiated, whereas the term "theory" suggests an overarching but tentative explanation of facts and laws, itself based on one or more hypotheses. An important difference between a theory and a measurement is that a measurement is usually associated with something observable and on this account is imputed a factual status, whereas a theory is usually associated with unobservables and so is seen as more dubious from an epistemic point of view.

Theoretical Concepts. Just as a metrical concept is associated with a measurement or measuring process, so a theoretical concept is associated with a scientific theory. In its complete formulation, however, a theory involves more than theoretical concepts or terms; it will also contain observable, metrical, and logical concepts, all bound together in a systematic account. And, just as metrical concepts combine elements of the physical and the mathematical, so theoretical concepts combine elements of the physical and the logical, and frequently of the mathematical as well.

The intriguing problem that presents itself in connection with a theoretical concept is whether it represents something that exists outside the mind, and so refers to a "real being" (Lat. *ens reale*), or whether its status is that of a logical construct, a "being of reason" (Lat. *ens rationis*) that exists in the mind alone and whose referent is a fictitious entity having no extramental existence (Sec. 4.6). When choosing between these alternatives, it is convenient to think of the referent of a theoretical concept as a mere "candidate for existence."[1] A resolution of the candi-

1. I owe this expression to Rom Harré, *The Principles of Scientific Thinking*, Chicago: The University of Chicago Press, 1970. In his more recent work, *Varieties of Realism*, Oxford: Blackwell, 1986, he refers to them as "objects of possible experience."

date's status is then achieved when one is able to disengage the physical content (or the physical-mathematical content) of the theoretical concept from the logical apparatus in which it is embedded—usually some type of hypothetical reasoning. If the concept cannot be so disengaged it remains problematical. In this event it may be thought of as a hypothetical concept, one that may or may not refer to an actually existing entity.

Hypothetical Argument. Since hypothetical reasoning plays a key role in adjudicating the ontological status of theoretical entities, we provide at this point a brief overview of the nature and validity of hypothetical argument. This type of argument has already been addressed in Chap. 4, where it was expressed in the logical form, "*If p, then q; and p; therefore q.*" Here we now introduce another logical relation, that of negation, and explain how it can be incorporated in various ways into this form. If we assume that proposition *p* stands for "This is lead" or "It is the case that this is lead," then the negation of this proposition, written *non-p*, stands for "This is not lead" or "It is not the case that this is lead."

Presupposing these notions, there are only two universally valid forms of hypothetical argument, which may be written as follows:

If p, then q; and p; therefore q (1)
If p, then q; and non-q; therefore non-p (2)

These may be illustrated respectively with the oft-cited examples: (1) "If it is raining, then the ground is wet; and it is raining; therefore the ground is wet"; (2) "If it is raining, then the ground is wet; and the ground is not wet; therefore it is not raining." In both cases, *p* may be referred to as the antecedent of the argument and *q* as the consequent. Then an argument of form (1) determines the truth of the consequent by establishing the truth of the antecedent, whereas an argument of form (2) determines the falsity of the antecedent by establishing the falsity of the consequent. For later purposes it is important to note that form (2) can be used in principle to falsify a hypothesis or antecedent in terms of the known falsity of the consequent, but form (1) cannot be used to verify a hypothesis or antecedent, since it assumes the truth of the antecedent in order to verify the consequent. Hence form (2) can be used to falsify a hypothesis, a process known as falsification, but form (1) cannot be used to verify a hypothesis, a process known as verification, although it has other uses, as will be explained presently.

Apart from the two valid forms of hypothetical argument just explained, there are two invalid forms that involve fallacies or fallacious reasoning. The fallacies are the following:

If p, then q; and non-p; therefore non-q (3)
If p, then q; and q; therefore p (4)

Examples of these, respectively, are the following: (3) "If it is raining, then the ground is wet; and it is not raining; therefore the ground is not wet"; (4) "If it is raining, then the ground is wet; and the ground is wet; therefore it is raining." Form (3) expresses the fallacy known as denying the antecedent and form (4) expresses the fallacy known as affirming the consequent. The reasoning in each case is fallacious, as can be seen by evaluating it in terms of the conditions that are necessary to have a valid argument. As stated, for example, the condition "if it is raining" is *sufficient* to explain the consequent, "the ground is wet," but it is not *necessary* to explain it, since the ground could be made wet by another cause, for example, sprinkling the lawn. A conditional statement, on its own terms, merely states that the antecedent is sufficient to explain the consequent, without asserting that it is necessary to do so. Applying this understanding of implication to form (3), we may see that eliminating the particular antecedent by stating *non-p* does not guarantee that *non-q* follows, for there might be some other antecedent or condition that would entail *q*, and thus the possibility of *q* is not eliminated merely by negating *p*. The same line of reasoning applies to form (4), since *p* again may not be the unique antecedent that entails *q*, and thus the assertion of *q* is not sufficient to warrant the affirmation of *p*.

For forms (3) and (4) to be valid as written, one would have to show that *p* is both sufficient and necessary to imply *q*, and then the antecedent would have to be stated in the stronger form,

If and only if p, then q; and . . . (5)

In mathematical logic the antecedent here is written *Iff p, then q*, where the implication *Iff . . . , then . . .* is known as equivalence. If one can employ this stronger antecedent, then forms (3) and (4) become equivalent to forms (1) and (2), and one is able to verify hypotheses as well as falsify them.

7.3 Hypothetico-Deductive Reasoning

As it turns out, the overwhelming majority of scientific arguments do not use any of the forms given above. Instead they use a form of reasoning referred to as hypothetico-deductive (HD), which has come to be regarded as the standard method to be used in scientific research. In HD method the investigator formulates a hypothesis that is capable of empirical test, and then designs an experimental procedure for verifying or falsifying consequences deducible from that hypothesis. The hypothesis (H) and the deduction (D) following from it explain why it is called HD method. After repeated instances of having confirmed or disconfirmed empirical consequences deduced from the hypothesis, the researcher is in a position to judge its validity. The more confirming instances he has, the more his hypothesis is verified; the more disconfirming instances, the more it is falsified or seen to be in need of revision. Since the hypothesis itself can be generalized beyond a statement of hitherto unknown fact to include a law or even a theory, and since consequences can be tested by a broad range of fact-finding techniques, ranging from experiments employing precise measurements to polls and questionnaires, the method is easily extended into all fields of inquiry. Additionally, since its testing procedures are repeatable by other investigators, HD method has come to be regarded as the most potent way of publicly verifying the knowledge claims of science. Thus it has been accorded the label "scientific method" and has become paradigmatic for investigative research in the natural sciences, the behavioral sciences, and the social and political sciences as well. Indeed, science itself is now defined by many as justified true belief, the terms "justified" and "true" referring to the verification afforded by HD method.

HD reasoning assumes a form that is similar to (4) in the previous section, and it may be written as follows:

If p, then q; and q; therefore possibly *p* (6)

This form is generally used when the entity or situation designated by *p* is not directly observable or measurable, whereas some other state of affairs that *p* would be sufficient to explain, namely *q*, is directly observable or measurable. In such an event one can use observation and experiment to identify possible realities that otherwise are unobservable and unmeasurable. The fact that a hypothesis entails a proposition whose truth is testable by measurement or experiment seems to lend support to accepting the truth of the hypothesis, at least as a real possibility.

Confirmation. Moreover, should one be able to formulate a hypothesis that has a large number of testable consequents, and should each of these consequents in turn be verified, one would be inclined to accept the truth of the hypothesis as more than possible, and even as probable. Such a situation suggests a type of argument that may be formulated differently than (6) and written

$$\textit{If } p, \textit{ then } q_1, q_2, q_3 \ldots q_n; \textit{ and } q_1, q_2, q_3 \ldots q_n; \quad \textit{therefore} \text{ probably } p \qquad (7)$$

Here the p, as previously, indicates the hypothesis, and the various q's, numbered from *1* to n, designate a series of consequents that are testable or measurable. When all of these, upon test, have been verified experimentally, and especially when the numbered consequents pertain to different domains of experience, the hypothesis would appear to be not only a real possibility but, in fact, probably true.

Finally, if an argument of form (7) can be combined with that of form (2) above, which will enable one to reject or falsify hypotheses that do not yield verified consequents, then it appears that a methodology has been set out whereby one can eliminate false hypotheses and at the same time retain those that are more and more confirmed and therefore have progressively greater chances of being true. Efforts have been made to calculate mathematically the degree of probability to be attached to a conclusion reached by this method, but it turns out that there is no simple way to do so. Rudolf Carnap, in particular, has devoted considerable efforts to devising an artificial language that would measure the degree of confirmation C afforded hypothesis H by evidence e, provided by the function $C(H,e)$. It is generally agreed, however, that these efforts have not met with success.[2]

Falsification. The logical stalemate to which the theory of verification had come is what provoked Karl Popper, mentioned in the previous chapter, to develop his theory of falsification. Popper focused on the truth-value asymmetry that is discernible between forms (2) and (4), where the falsification of the consequent in (2) yields a true result whereas the verification of the consequent in (4) yields only a fallacy. For him, therefore, form (2) provides the paradigm for scientific argument, one to be favored over the fallacious form (4) or its corrected versions, forms (6) and (7). This provides the basis for his program of "conjectures and refutations" referred to above in Sec. 6.5.

Even this Popperian revision, however, seems unable to eliminate the element of probability that appears to be endemic to hypothetico-

2. See, especially, his *Logical Foundations of Probability*, Chicago: University of Chicago Press, 1950. A brief sketch is given by Losee, *A Historical Introduction*, 195–196; see also Sec. 7.6 below.

deductive explanation in both its verificationist and falsificationist forms. The flaw in his falsificationism has been pointed out by Willard van Orman Quine, using arguments anticipated in the writings of Pierre Duhem, to formulate what has become known as the Quine-Duhem thesis. This recognizes that, though in the ideal case form (2) is logically correct, in actual scientific practice the program it entails proves impossible to carry out. What prevents it from working is the complexity of modern theories and the large number of suppositions they are forced to employ in the antecedent. Instead of form (2), one has in fact to deal with a conditional argument such as the following:

$$\textit{If } p_a, p_b, p_c \ldots p_i, \textit{ then } q; \textit{ and non-}q; \textit{ therefore non-}p_? \qquad (8)$$

In this situation, with q falsified it would follow that some part of the antecedent must be false also. But precisely what part of p is false, the *non-*$p_?$, of (8), proves difficult to ascertain and indeed cannot be determined with any degree of probability. Thus neither Carnap's nor Popper's program can achieve certainty, and one is left with the conclusion that modern scientific reasoning yields, at best, a probable result.

Despite this limitation, scientific practice in the present day combines the techniques of confirmation and falsification implied in forms (7) and (8). Through their use the considered judgment of scientists, or of the scientific community, accords many propositions that are so confirmed a degree of verisimilitude approaching truth, and they are commonly regarded as constituting the body of scientific knowledge.

7.4 Theoretical Entities and Their Modeling

To return now to theoretical concepts, such concepts initially have the status of hypothetical concepts or constructs formulated or constructed as part of a hypothesis. They generally function also as explanatory concepts, since they serve to explain why certain statements, basically those employing observable or metrical concepts, are true or are thought to be valid generalizations. The theoretical concepts that are of particular interest for scientists are those that designate theoretical entities—already spoken of as candidates for existence. Some examples taken from the physical sciences may clarify how such entities enter into scientific discourse, and additionally, how they can have an important modeling function in providing an insight into the structure of reality, particularly in the regions of the very small, the microcosm, and the very large, the megalocosm.

Theoretical Entities. The observable features of things, such as yellow, heavy, and hot, have aroused curiosity for centuries, so that it is not surprising that the history of science is replete with explanatory concepts that have been proposed to account for them. It is not unusual that such explanatory concepts have associated with them hidden or unseen entities, and thus the problem arises whether these entities are mere fictions created by the mind or whether they exist, or at least have counterparts that exist, outside the mind. For instance, to explain why some objects of experience burn more readily than others, it was early hypothesized that the combustible objects might contain more of an invisible substance known as phlogiston, which had some peculiar properties such as negative weight, than the other objects. Later, on the basis of experiments performed with combustible substances, the hypothesis was offered that a quite different substance called oxygen, also invisible but with a positive weight, could explain most of the phenomena that phlogiston had previously been invoked to explain. Again, rather than propose that heat itself is caused by the presence of a substance whose essence is to be hot, such as caloric or phlogiston, it was further proposed that heat might be caused by the motion of the minute particles of which material substances are composed, called molecules. This last proposal, referred to as the kinetic theory or the molecular theory of heat, is accepted in the present day as the best explanation of ordinary phenomena involving the generation of heat and the presence of varying degrees of heat in the objects of experience.

The theoretical concepts "phlogiston," "oxygen," "caloric," and "molecule" all designate entities whose existence is not immediately apparent but which, because of their explanatory force, were regarded by those who first proposed them as candidates for existence. With the progress of science, however, "phlogiston" and "caloric" have come to be regarded as concepts that designate fictive entities, mere beings of reason, and are no longer thought of as real substances. On the other hand, "oxygen" and "molecule" have enjoyed a better fate: they are still mentioned in science textbooks, and most scientists think of them as just as real as the objects of ordinary experience. Hence "phlogiston" and "caloric," which were first proposed as parts of logical schemata of the type "if p, then q," have been relegated to the same domain as the logical concepts with which they were first associated, whereas "oxygen" and "molecule" have seemingly passed out of the logical domain and are now entertained as real concepts, as having extramental counterparts to the same degree, say, as sulphur and lead.

Similar examples may be drawn from the field of astronomy. At one time, in order to explain the seemingly erratic movement of the planets against the background of the fixed stars, it was hypothesized that planets are carried along by an elaborate series of rotating circles or mechanisms referred to as "eccentrics" and "epicycles." Astronomers argued about the ontological status of these rotating mechanisms, some proposing that they were merely convenient fictions that enabled one to calculate the positions of the planets, others regarding them as real and speculating about the materials of which they might be composed and how they could propel planets along in their orbits. Later, after detailed observations of the planet Mars had been made, it was argued that planets move in paths that are elliptical, and that their motions can be explained on the supposition that planets are massive objects like earth, urged along by the "force of gravity" and "inertia." Again, to explain irregularities in the motion of the planet Uranus, it was hypothesized that these were caused by the gravitational attraction of a planet farther out in the solar system, then unknown but subsequently discovered and named "Neptune." Alternatively, to explain irregularities in the motion of the planet Mercury, it was postulated that these were caused by a hidden planet, called "Vulcan," too close to the sun to be observed, but nonetheless a candidate for existence.

Here, as in the previous cases, some of these theoretical entities have survived the passage of time and are now thought to have real existence as well as explanatory value, whereas others have been discarded as constructs that at one time were useful for predicting phenomena but no longer enjoy extramental existence. So, one no longer finds mention of "eccentrics," "epicycles," and "Vulcan" in astronomy textbooks, whereas "force of gravity," "inertia," and "Neptune" remain part of the science of our day.

The problem of how to disengage a theoretical concept from the hypothetical schema in which it was first entrenched and see it as designating a really existing entity will be addressed in the following chapter. Usually such disengagement requires an ostensive demonstration, which is equivalent to developing an "if and only if" type of argument that replaces the antecedents in forms (1) and (4) with that shown in form (5). Another possibility is a negative demonstration or indirect proof that enables one to reject hypothetical entities as merely fictive and so devoid of extramental existence.

Apart from these two ways of dealing with theoretical entities—namely, that they either are accepted into the domain of the real along with more directly observable and measurable objects or are rejected from this domain and relegated to that of the logical—there is the final possibility. The entity may remain simply a candidate for existence, retaining a problematic status somewhere between the real and the logical, but not yet accepted with certainty by the scientific community. "Quarks" and "black holes" are entities of this latter type, and one can readily understand why they provoke great interest and discussion among scientists and philosophers alike. For purposes here it may suffice to explore an additional epistemic value of these problematic entities, namely, their use in modeling the real and thus as supplying analogical insights into the structure of matter and the universe.

Modeling the Real. The modeling value of theoretical concepts may be illustrated with the aid of a homely example, that of the "mermaid." It is sometimes said that mermaids were thought to exist because sailors, after long months at sea and when observing under adverse conditions of distance and at dusk, saw beings nursing their young at the breast, with long hair and fish-like tails that came into view when they dove beneath the surface. To explain these appearances, the sailors constructed an explanatory concept by putting together two concepts of which they had previous experience, namely, "fish" and "woman," and arrived at the construct "mermaid." On this account "mermaid" became a candidate for existence, but not existence in a complete and absolute sense, because the sailors were sure that they had observed something, though they were not sure of what it was. Their problem focused on the nature rather than on the existence of what they had seen, and hence their construct was formulated to explain the entity's nature rather than its existence. The problem was ultimately solved with the identification of a species called the dugong, which, when viewed under conditions approximating those of sailors at sea, were found to explain the phenomena they had observed. Dugongs nurse their cubs at the breast, they have blubber around their necks that in silhouette conveys the impression of long wavy hair, and they have tails like those of fish.

A somewhat similar situation exists with the theoretical entities known as elementary particles, an example of which would be the electron discussed in Sec. 2.2 and elsewhere. The "electron" is a very useful concept for explaining electrical and magnetic phenomena, to say nothing of light and colors, such as the yellow beam emitted by the sodium atom (Sec. 2.3). As a theoretical entity it enjoys a status much like that of the "molecule," for it is now generally accepted among scientists as having extramental existence (see Sec. 9.7). But some years ago, when trying to discover more about the nature of electrons, investigators encountered puzzling phenomena, including some in which electrons behave like waves and others in which they behave like particles. To explain these phenomena they formulated a construct that combines features of both, and so gave rise to the theoretical concept "wave-particle." Obviously, one can go on from this and formulate a proposition such as "The electron is a wave-particle." And "wave-particle" turns out to be a very useful construct, for it suggests numerous calculations and predictions that can render an account of the metrical aspects of electronic phenomena, most of which can be tested experimentally and verified according to form (6) of the hypothetical reasoning explained above. Yet despite such extensive verification, "wave-particle" remains a problematic concept, one still enmeshed in the logical apparatus of a form (6) type of reasoning. Its status is only probable, even though the existence of the entity designated as an electron may be quite certain. The point to be made, therefore, is this: granted that "wave-particle" does not tell the whole truth about electron, it does furnish an insight into what an electron might be. It is in this sense that "wave-particle" might be thought of as modeling the electron in much the way "mermaid" functioned in a preliminary modeling of the dugong.

Theoretical constructs of this type are useful for investigating the domain of the very large as well as that of the very small. For example, it is generally acknowledged that planets and stars are massive objects in the heavens, that they have weight or gravity. Now, although "weight" and "gravity" are concepts that seem to be well understood, the cause of gravity has turned out to be more problematic. In that connection Newton spoke of "gravitational attraction" and even speculated as to whether or not the "pull of gravity" is real, but he did not commit himself to a definitive answer (see Sec. 10.6). Some two and a half centuries later, after having studied gravitational phenomena more extensively, Einstein proposed a quite different explanatory concept. He did so by adopting a suggestion of his teacher Hermann Minkowski, who took the two well-known concepts "space" and "time" and combined them to formulate the theoretical construct "space-time."[3] From this followed mathematical calculations and predictions, much like those generated by the construct "wave-particle." These have subsequently been verified, and they give "space-time" a probable status analogous to that of "wave-particle." Yet one need not hold that "space-time" is fully real, for that concept likewise gets its meaning and intelligibility only in the context of form (6) type of reasoning. It is generally acknowledged also that such a con-

3. In his 1908 address, "Space and Time," translated and reprinted in *The Principle of Relativity*, New York: Dover Publications, n.d., pp. 73–96.

struct furnishes some insight into the reality behind gravity and gravitational phenomena, much as did Newton's earlier construct of "pull of gravity" that dominated physics throughout the eighteenth and nineteenth centuries.

7.5 A Fuller Typology of Concepts

In Section 4.6 we have already explained how concepts are formed by the mind through a process of abstraction, and how these fall into different types, depending on the degree of abstraction involved in their formation. We have also distinguished real concepts from logical concepts and then shown, in our "Basic Types of Concepts" (Fig. 4.4), how all these concepts are related to extramental reality. It is now desirable to add to this earlier listing the additional types of concepts that typify scientific discourse.

Fig. 7.1 draws together all of this material. It is similar to the earlier typology of Fig. 4.4 in that it includes most of the entries from the previous table, with scientific concepts now added. The "outside mind" entries appear in the first column of both figures, but in Fig. 7.1 they are identified as in the perceptual order and are expanded from the "this yellow sulphur" and "this lead ball" of Fig. 4.4 to further include "this planet Mars" and "this sea mammal." Physical concepts have likewise been expanded in Fig. 7.1 to occupy the three middle columns, labeled observable, metrical, and theoretical respectively, each of which now requires amplification.

The observable column lists concepts directly associated with the sensations and percepts of the four objects perceived, those listed in the first column. Thus "sulphur," "yellow," and "element" are concepts that can be used to characterize "this yellow sulphur," the first identifying it as a substance, the second noting its color, and the third, its status as a chemical element. Similarly "lead," "heavy," and "cold" are concepts associated with "this lead ball," the first identifying the material in the ball, the second its weight, and the third its temperature. Again, "planet," "movement," and "oval path" are presented as concepts associated with "this planet Mars," the first specifying it as a planet, the second noting its motion, and the third, that this motion is in an oval path. And finally "woman," "fish" and "dugong" are shown as concepts suggested by "this sea mammal," the first two noting substances to which it bears a resemblance, and the third identifying the natural kind to which it belongs.

The metrical column builds on the observable column and lists on several of the rows measurements that correspond in one way or another

Types of Concepts—II

Outside Mind **Extramental** **Reality**	**Inside Mind** **But also exists in some way outside mind** **REAL CONCEPTS**			**Inside Mind** **But not** **outside mind**
Perceptual **Order**	**Physical Concepts**			**Logical** **Concepts**
	OBSERVABLE	METRICAL	THEORETICAL	
this yellow sulphur	sulphur yellow element	5745 Å	←molecule ←electron ←wave particles→	*p* *non-p* *p and q*
this lead ball	lead heavy hot	7.2 cm. 524 cm. 70°	←pull of gravity→ caloric→	*if p, then q; and* *p; therefore q*
this planet Mars	planet movement oval path	ellipse	eccentrics→ epicycles→ ←space-time→	*if p, then q; and* *non-q;* *therefore non-p*
this sea mammal	woman fish dugong		mermaid→	*if p, then* $q_1, q_2,$ $\dots q_n$*; and* $q_1, q_2, \dots q_n$; *therefore* *probably p*
	Mathematical Concepts sphere five set			*zero* *null-set*

Fig. 7.1 Additional Types of Concepts

to the perceived objects. The "5745 Å" thus measures the wavelength of the yellow light emitted from a sodium vapor lamp. The "7.2 cm." measures the diameter of the lead ball, the "524 g." its weight, and the "3° C" its temperature. And the "ellipse" specifies in a precise way the geometrical path followed by Mars in its oval motion.

The theoretical column then adds a selection of concepts or constructs that serve to explain observable or metrical features shown in the columns on its left. In listing these, arrows have been added to each of the concepts to suggest alternate possibilities, namely, that they are now generally regarded as real (thus: "←molecule," with the arrow pointing toward the left), or that they are now thought of as beings of reason similar to logical concepts (thus: "caloric→," with the arrow pointing toward the right), or that they designate entities with a problematic status whose ontological reference is still undecided (thus: "←wave-particle→," with arrows pointing in both directions). More specifically, with regard to the yellow sulphur, "molecule" may be applied to the natural minimum of that element, "electron" to the part of that minimum that emits a yellow light when in an excited state, and "wave-particle," to the electron itself. With regard to the lead ball, its weight might be explained in Newtonian terms by the "pull of gravity" and its lack of heat by the absence of "caloric" in its interior. The movement of the planet Mars would be explained in Ptolemaic terms by "eccentrics" and "epicycles," or in general relativity by a geodesic in "space-time." "Mermaid," finally, is the fictive entity spoken of by sailors, whose real foundation was putatively the dugong seen at a distance and under dim lighting conditions.

Mathematical concepts appear in the middle column listing real concepts, directly under the physical concepts, just as those shown in Fig. 4.4. They are set off from both physical concepts and logical concepts—more abstract than the former and yet not as "mind-dependent" as the latter. This allows the possibility of inquiring about the status of the concept of "sphere," as in the propositions "The earth is a sphere" and "Imagine a perfect sphere," or of the concept of "five," as in the sentential contexts "There are five crystals of sulphur" or "Five is an odd number."

Do "sphere" and "five" have real existence in the way that "subject" and "predicate" do not? In a sense they do, for the earth's shape is spherical and its sphericity exists "mind-independently" as much as does the earth, and the "five" designates something about the objects to which it applies, and in so doing shares in their reality. In another sense their being is not as manifest as that of the earth and its objects, for although some astronauts have seen the sphericity of the earth, no one has seen a perfect sphere, and although everyone may have seen five objects someplace, one may well wonder about the existence of five as a pure number. The implied difficulty can be taken care of by regarding the perfect sphere and the pure number as abstract entities, the *ens quantum* of the Aristotelians, abstracted from sensible matter and yet involving imaginable or intelligible matter in their very conception. On the basis of the adage *abstrahentium non est mendacium* ("those abstracting are not lying"), one might hold that statements employing mathematicals can be true of the real world, even though the entities they designate have no separate existence when considered in abstraction from the real world.[4]

A similar problem is presented by another term listed along with mathematical concepts, but in the column on the far right, namely, "zero." Were one to say, "There are no people in the room," or, "The number of people in the room is zero," what is the existential status of the "zero"? An Aristotelian might reply that zero used in this sense is not a number, that it is rather the negation of a number and thus has more the character of *non-ens*, a logical construct, than it has that of *ens* or even of *ens quantum*. The same might be said of "null-set," the negation of the concept of "set," the generalized equivalent of whole number and thus shown along with "five" under the real concepts. It should be noted that urging this distinction between the real and the rational is not done to bar logical constructs from the realm of the mathematicals. All that it means is that such constructs are not admitted on the basis that they are abstracted from the sensible world. Rather they have a foundation in sense knowledge, a *fundamentum in re*, and this would seem to suffice for their consideration by the mathematician.

It should be noted that the metaphysical concepts listed under the real in Fig. 4.4 have not been transferred to Fig. 7.1, since they have no immediate relevance to the scientific concepts being discussed in this section.

To move finally to logical concepts, the "inside mind" entries in the last column of Fig. 7.1, these are similar to those in Fig. 4.4 except that now only expressions from propositional logic have been retained. Here the listing of the various logical forms is not intended to be correlated with the rows of the other columns. They are shown merely as illustrative of the types of logical propositions in which theoretical concepts are frequently embedded.

It goes without saying that theoretical concepts are the concepts that generate most of the literature in the philosophy of science. Observable and metrical concepts are more or less taken for granted, and logical concepts essentially provide the framework in which theoretical concepts can be understood and possibly adjudicated for their extramental existence.[5]

4. Penelope Maddy makes much the same point in her *Realism in Mathematics*, Oxford: Oxford University Press, 1990, chap. 3.

5. This close connection between logical forms and theoretical concepts perhaps explains why Carnap viewed theories in science as partially interpreted formal systems, as noted in Sec. 6.4.

7.6 Causation, Event Ontology, and Probability

Most of the discussion of probable reasoning to this point has been concerned with the logical analysis of arguments, inspired, one might say, by the "logical" component of logical empiricism. It remains now to look at the "empiricism" component, for this too inserts a note of skepticism into the thought of logical empiricists and causes them to shy away from any apodictic claims in the science of nature. In this matter they take their lead from David Hume. As explained in Sec. 6.1, Hume elaborated a sensist theory of knowledge that denies reality to the concept of substance and makes it impossible to discern any necessary connection between a cause and its effect. On the basis of this theory of knowledge, Hume rejected causality in its traditional understanding, although he retained the terminology of cause and effect and incorporated them into the new relationship he referred to as causation. Hume's antimetaphysical attitude had great appeal to philosophers in the early twentieth century who were reacting to the idealism of Kant and Hegel, and his views have exerted considerable influence within the philosophy of science movement ever since.

Causation. Before Hume, the English philosopher John Locke had started the move toward skepticism by questioning whether science could ever attain necessary knowledge of nature. Under the influence of Isaac Newton, Locke was attracted to a corpuscular theory of matter and proposed that the "real essence" of bodies consists in the configurations and motions of the atoms of which they are composed. Were we to know the "powers" with which these atoms are endowed, he speculated, we would be able to explain the various properties of bodies in strict scientific fashion. But these powers unfortunately are hidden from us, and the extreme minuteness of the atoms themselves precludes our ever attaining knowledge of them. So we must settle for descriptions of the properties and attributes of bodies, what Locke termed their "nominal essences," as these can be ascertained from the study of natural histories along lines earlier suggested by Francis Bacon. The generalizations these would provide are probable at best, and so for Locke it would be illusory to think of necessary truth as the goal of natural science.

Hume went a step beyond Locke by arguing that, even if we were to know atomic arrangements and interactions, we still could not have certain knowledge of how they produce sensible effects in the bodies of which we have experience. The basic principle behind this contention is that all human knowledge of matters of fact is given in, and arises from, sense impressions. But rather than focusing on the source of such knowledge in the essences of bodies and their powers, as Locke had done, Hume turned instead to examining how necessity could be found in sequences of events. To establish a necessary connection between events, he argued, one would have to prove that the sequence in which the events occur could not be otherwise. But such a proof cannot be found in experience, for we have no sense impression of any force or power by means of which one event will be constrained to produce another. Even though past experience indicates that events of type A are invariably followed by events of type B, there is no way we can logically conclude from this experience that the next A will necessarily be followed by a B. We can always imagine the opposite sequence taking place.

Through this type of argument Hume brought into question the key notion of causal efficacy or causal influence, the necessary connection between cause and effect implied in the traditional concept of causality. But he still wished to retain causal terminology, and so he proposed to reformulate the causal relation in different terms—giving rise to his new concept of "causation." In causation two components, temporal priority of cause over effect and constant conjunction between the two, replace the classical idea of causal efficacy. And, where previously there was thought to be an ontological link between cause and effect, Hume now proposed to replace this by a psychological link. For him, a causal sequence is one in which, upon appearance of an event of type A, we are led to anticipate an event of type B. Solely on the basis of such anticipation are we able to label A-events "causes" and B-events "effects." So, subjectively, the causal relation resides in our anticipation of what is going to occur when we see an event of the first type; objectively, nothing more than temporal priority and constant conjunction are required to characterize the relationship between the two types of events.

This is not the place to critique either Locke's or Hume's theory of knowledge, but one observation may be permitted here on the basis of material covered earlier in Sec. 4.8. In both of these theories the knower is proposed as knowing sense impressions or ideas, not as knowing things. Epistemologically this reduces very quickly to solipsism, for one can well have an impression and yet have no notion whatever of the reality to which the impression might correspond. In the Humean view, it seems that knowing becomes very much like imagining, and real concepts become very much like logical concepts. But we can always imagine sequences of events that are different from those in reality, and unfortunately what is regarded as logical necessity frequently bears little relation to the necessities found in the real world.

Although Hume's account of causation is usually given in terms of events, as it has been above, it should be observed that he himself frequently interchanges "object" with "event" when explaining it, apparently not recognizing the considerable difference between the two. This usage notwithstanding, he generally regards a sense impression as the equivalent of an event. Since he explicitly rejects the notion of substance, it is difficult to see how "object," for him, could refer to a substance or a subsistent thing. He seems to see impressions or the acquisition of simple ideas simply as events in the mind, and then straightaway projects them outside the mind as events in the real world. One consequence of this is that science, in Hume's view, can only describe sequences of events, and so the logic it requires must be propositional, based as it is on hypotheses about successions. This then takes the place of a logic of terms, which, as will be seen in the following section, is necessary to sustain causal inquiry in the traditional sense.

Event Ontology. A further consequence is that Hume, to the extent that he as a skeptic can have an ontology, is committed to an ontology of events rather than an ontology of things. Now an event ontology brings with it serious problems that continue to resist solution within the Humean tradition. If science is limited to statements about successions of events, and of past events at that, and if these statements are exhaustive of our knowledge of nature, then no statements about hitherto unobserved events of similar types can ever be regarded as true. In other words, generalizations that extend beyond what has actually been observed are simply excluded from science—a statement that surely would not apply to much of what is regarded as science in the present day. This is but an alternative way of formulating one important part of the Humean heritage, the so-called "problem of induction."

Another part of that heritage derives from the alleged independence of events in the Humean scheme. One event must succeed another, and, although in conjunction with it, cannot be known as connected to it. What this implies is that one event must have ceased to exist before another in the sequence can come to be. Hume's analysis prohibits any carry-over, and so the next event must always have an accidental or fortuitous character. Simply put, any event can come after any other, because there is no causal connection between them. And again, the science of the present day seems dedicated to showing that such is not the case. Some events may be truly accidental or fortuitous, but these are not the events with which science is concerned. Rather, it is events that are ordered and regular, that are predictable and repeatable, that constitute the subject matter of scientific research. This is the other enigma Humeans have to face, the "problem of causation," when constant conjunction is posited as a believable surrogate for causal efficacy.

Probability. From these observations it is easy to see why logical empiricists, and particularly those who take Hume as their guide, are committed to the view that all scientific reasoning is probable at best and fallible in the long run. Perhaps for this reason they devote considerable attention to the study of probability and how this notion can be used in the verification or confirmation of science's results. The most important development in this area, and one that produces a considerable literature within the philosophy of science, is the application of mathematical theories of probability to the confirmation of scientific theories.

Here again, events supply the model in terms of which theories or propositions are to be evaluated. A few examples may serve to illustrate the techniques that are used. Usually a calculus of probabilities is set up wherein probability is taken as a relationship between events of two different types, designated as u and v respectively. Event v might be the tossing of a die and event u the coming up of a particular number, say three, or v, drawing a playing card from a deck and u, getting a particular kind of card, say, an ace, or even a particular card, the ace of spades. The probability $P(u,v)$, that is, the probability of event u occurring given the antecedent event v, can then be calculated using fairly simple mathematics. For this, at least two assumptions are required: first, that there is only a finite number of possibilities (only 6 sides to a die, only 52 cards in a deck), and second, that all events are equipossible or equiprobable (the die is not "loaded," the deck is not "stacked").

Substituting propositions for events, one might speak of the probability of propositions being true, say $P(p,q)$ in the context of an argument of form (6) in Sec. 7.3: *If p, then q; and q; therefore probably p*, where the *possibly* in the former expression has now been replaced by *probably*. This is equivalent to inquiring into the probability of p being true on the basis of q being verified as the supporting evidence. Since p here is a hypothesis and q the alleged evidence in support of it, one may substitute h and e for the p and q respectively to obtain $P(h,e)$. But then P, the probability of being true, may be replaced by Carnap's operator or functor, C, standing for confirmation. The same expression may then be written $C(h,e)$, which becomes the degree of confirmation of hypothesis h

provided by evidence e. When several kinds of evidence are alleged in support of a hypothesis, moreover, this is equivalent to form (7) of a propositional argument in Sec. 7.3. In this case $q_1, q_2, q_3, \ldots q_n$ replaces q, and p replaces h and $e_1, e_2, e_3 \ldots e_n$ replaces e in $C(h,e)$.

Assuming a complete isomorphism between $P(p,q)$ and $C(h,e)$, it should be possible to calculate degrees of confirmation of hypotheses using the same mathematical rules as are valid in the calculus of probabities. One such rule, formulated by English minister Thomas Bayes in 1763 and so referred to as Bayes's rule, enables one to calculate a probability of the type $P(p,q_1$ and $q_2)$, where q_2 is evidence acquired after q_1. Those who invoke this rule, known as Bayesians, see it as casting light on the changes of truth-probability, and thus of confirmation, with the introduction of new evidence. The q_2 is in effect the equivalent of e_2 in support of hypothesis h, since the subscript n in form (7) here becomes equal to two—there being only two pieces of evidence, q_1 and q_2, given in support of p. The assumption of complete isomorphism in this enterprise, however, is very questionable, seeing that propositions (and particularly propositions involving theoretical concepts) are not events, they are not finite in number, and there is simply no way in which they can be regarded as equipossible or equiprobable.[6]

Considering this limitation, it is really surprising how much of the literature in the philosophy of science is devoted to the discussion of probability, statistics, decision problems and maximum-minimum problems, as though these constitute the essence of scientific reasoning. But whatever the value of such discussions, they do confirm the view being advanced in this chapter, namely, that in the modern mind science is identified with probable reasoning.

7.7 Knowledge, Opinion, and Belief

An important byproduct of the foregoing discussion of theoretical concepts and probability is that it highlights a point long recognized in the Aristotelian tradition, namely, the dialectical or probable character of knowledge based on remote premises such as common logical principles. On this account it is worth the effort at this point to clarify the differences in that tradition between (1) the type of knowing that is characteristic of *scientia* in the strict sense, (2) the type of knowing that is in-

6. Here we follow the exposition of John Earman and Wesley Salmon in their *Introduction to the Philosophy of Science*, pp. 66–99; see also Losee, *Historical Introduction*, pp. 244–250.

duced by reasoning that is logically probable, and (3) the type of knowing that results from persuasive argumentation. These are known as knowledge, opinion, and belief respectively.

Types of Knowing. Aristotle's term for knowledge is *epistēmē*, and by this he intends a type of perfect knowing that may be expressed in certain and necessary conclusions. Norms for attaining this type of knowledge are set out in the *Posterior Analytics*, as pointed out earlier in this study (Sec. 6.7). The Greek term *epistēmē* translates into Latin as *scientia*, science in the strict sense, which attains truth with certitude and sets the ideal toward which scientists aspire even in the present day. Admittedly the ideal is difficult to achieve, and throughout history investigators of the world of nature have had to content themselves with a lesser goal—knowledge that is probable, though not absolutely certain. The Greek term for this type of knowing is *doxa*, and it translates into Latin as *opinio*, usually rendered into English as opinion. To have opinion in this sense is to assent to a proposition rather than to its opposite, but with an awareness that the proposition might be false and the opposite true. Norms for attaining probable knowledge of this type, also referred to as dialectical or verisimilar knowledge, are explained in Aristotle's *Topics*. Yet a third type of knowing is even less firm than opinion; this occurs when a person cannot decide between two contradictory propositions and yet inclines to accepting one over the other. The Greek term for this type of knowing is *pistis*, and it translates into Latin as *fides* or *persuasio*. The English equivalent would be belief or persuasion. Norms for inducing this type of assent are worked out in Aristotle's *Rhetoric*. Whereas the *Topics* establishes norms for discerning probabilities based on logic, the *Rhetoric* takes into account ways in which people are additionally persuaded by appeals to the emotions and to the authority or character of the one persuading.

In the present chapter the focus is on science as probable reasoning, leaving the possibility of science as demonstrative or epistemic for consideration in the following chapter. As already noted, the consensus concerning recent science is that its results are always provisional or fallible and therefore always subject to revision. On this understanding, within an Aristotelian context modern science would be considered a species of opinion, highly probable opinion perhaps, but opinion nonetheless. Whether this judgment would apply to the entire content of science or only to the great majority of its conclusions need not be addressed here, since it will be considered in the next chapter. During most of modern science's history up to the end of the nineteenth century, however, scientists generally subscribed to the traditional notion of science as certain and necessary knowledge. The fallibilist view seems to be a twentieth-century development, prompted largely by advances in physics associated with quantum theory and the theories of relativity. Toward the end of the twentieth century, moreover, the situation has been further exacerbated by the proposal that science itself is to be identified with rhetoric. Rather than say that science is opinion, some would maintain that it is essentially belief. They may add the qualifiers "justified" and "true" to the "belief," but considering the special meanings that attach to these qualifiers this does not substantially alter the fiduciary character thus attributed to the scientific enterprise. And, although the "rhetorical" aspect of modern science was initially prompted by the way scientists package and present their results in the late twentieth century, the thesis has been enlarged to apply to the entire history of science. On this view, some would hold that all of science is said to be "socially constructed," facts no less than theories, and for them persuasion comes to be regarded as the principal vehicle for science's acceptance.

Within an Aristotelian context, as has been said, modern science would be regarded as a species of opinion, namely, highly probable opinion. It should be pointed out, therefore, that for Aristotle opinion *(doxa)* is not a monolithic notion but one that permits of degrees. The highest degree of opinion, and the one that most closely resembles truth in its verisimilitude, is what Aristotle calls *endoxa*, a term usually translated as reputable opinion or expert opinion. In many texts Aristotle accords *endoxa* a factual status, equating them with *phainomena* or perceived appearances and so putting them on a par with empirical data. Similarly he expands his notion of truth to include truths that are partial and obscure, and points to such truths as those that are contained in, or attendable from, *endoxa*.[7] Aristotle also insists that probable or dialectical reasoning of the type he explains in the *Topics* is necessary for establishing the principles on which epistemic knowledge is based. Thus he allows for a transition from probable knowledge to certain knowledge, from dialectics to demonstration, as one gains progressively truer and clearer knowledge of a particular subject matter. How such a transition may be effected will be touched on at different places in the chapters that follow.[8]

7. An illuminating discussion is contained in Kurt Pritzl, "Ways of Truth and Ways of Opinion in Aristotle," *Proceedings of the American Catholic Philosophical Association*, 67 (1993), pp. 241–252; see also his "Opinions as Appearances: *Endoxa* in Aristotle," *Ancient Philosophy* 14 (1994), pp. 41–50.

8. See particularly Sec. 8.5 and the discussion throughout Chap. 10.

A Logic of Terms. To explore further the relationships between knowledge, opinion, and belief, it is necessary to move beyond propositional logic, which considers the proposition as the basic unit of analysis, to a logic of terms, which breaks the proposition down into its components and thus is able to expose its contents. In this way one can more readily move from a formal logic to a material or content logic. Subjects of predication can be identified, and so can their predicates. More importantly, between the subject term (S) and the predicate term (P) in the conclusion of an argument or proposed proof, one can insert the reason or cause that explains why the two terms are joined together. This third term is called the middle term (M). In effect, then, the argument is shown to be reducible to a statement of the type "S is P, because M."

A further analysis of this type of statement can be made by placing it in the form of a categorical syllogism. Actually there are several ways in which this can be done, but for purposes here the most important form is the following: "M is P; and S is M; therefore S is P," where, as above, S and P are the subject and predicate of the conclusion and M is the middle term. The propositions "M is P" and "S is M" are the premises of the syllogism. The first of these, "M is P," is called the major premise because it contains P, the term which usually has the broadest extension of the three, whereas the second, "S is M," is called the minor premise because it contains S, the term usually with the narrowest extension. "S is P," as has been said, is the conclusion that is entailed by the premises, the consequent of the argumentation in which the two premises form the antecedent.[9]

Using this simple schema it is possible to clarify the essential differences between knowledge (in the strict or epistemic sense), opinion, and belief. The first requires that a necessary ontological connection be seen to exist between subject and predicate, the second that probable logical reasons be offered for joining them together, and the third that apart from logical considerations there be other persuasive reasons for doing so. Another way of stating the differences is to focus on the subject matter with which the reasoning is concerned. In view of the "necessary connection" requirement, scientific reasoning is said to be concerned with necessary matter, whereas opinion and belief are said to be concerned with a contingent subject, with matter that could be otherwise. Because of the possibility of the conclusion being otherwise, it is essen-

9. Instead of "If *p*, then *q*," with *p* being the antecedent and *q* the consequent, we then have the more articulated form, "If M is P and S is M, then S is P," which enables the middle term or connector to be identified and the force of the inference to be properly assessed.

tial to the notions of both opinion and belief that they be accompanied by a fear or reservation that what is being assented to is not true. On this account it is possible to have opinion about a necessary matter that is not recognized as necessary but seen as only contingent, for then fear of the opposite would again be present. So a person presented with a scientific demonstration that the sun is larger than the earth might not understand the demonstration. In that case he would have only opinion on the matter, whereas a person who understood the demonstration would have scientific knowledge of it.

The foregoing obviously applies to conclusions arrived at by a reasoning process and is not intended to apply to facts that are known and accepted on simple human faith. In the latter case fear or reservation does not enter into the acceptance, unless there is reason to be suspicious of the source as not completely trustworthy. Most of what the normal person knows about geography and history, or what an investigator accepts as data from collaborators, or what the average scientist knows about fields other than his own, is known by simple faith—as facts that are certain. On the other hand, conclusions that are established only by hypothetico-deductive reasoning of the types expounded by Carnap and Popper lack this certain character, since the logic of inquiry in each case leaves room for doubt. The conclusions arrived at might not be true, and thus the inquirer ends up with opinion and not with scientific knowing in the strict sense.

Hypothetical arguments expressed in forms (1) through (4) and (6) through (8) of Sec. 7.2 are known as hypothetical or conditional syllogisms, and they are different from categorical syllogisms, in which middle terms can be identified and their probative force directly assessed. Within an Aristotelian framework the norms for the types of reasoning they involve are treated in the *Topics*, as has been mentioned. On this account they are referred to as topical or probable arguments. These arguments are of various kinds, not limited to the hypothetical types already discussed, as will now be detailed.

7.8 Topics and Probable Reasoning

Just as science or knowing in an unqualified way is produced by the demonstrative syllogism, so opinion is produced by a probable or dialectical syllogism. A syllogism of this type is composed of probable propositions, that is, propositions that are verisimilar and worthy of acceptance as probably true. Everyday examples would be that parents love their children, that people prefer to be rich rather than poor, that shoppers want a bargain; more philosophical examples might be that the universe is one, or that it had a beginning, or that the good in itself is preferable to the merely useful. A syllogism composed of probable propositions, or of a probable proposition and a necessary proposition, or of a necessary proposition that is regarded as probable, is said to be dialectical. Such a syllogism need not be concerned with contingent matter, for even one concerned with necessary matter is only probable if it is not seen as necessary.

The Notion of Topic. The middle term of a probable syllogism is known as a topic or place (from the Gr. *topos*, Lat. *locus*), suggesting a place from which one can draw an argument. In common usage the term "topic" usually refers to the argument itself, not where it is found, and may be defined as a probability enjoined to induce assent. It is joined verisimilarly either to the subject and predicate of a question or to one or the other so as to gain acceptance of the position being argued, though without necessity. In this, the dialectical argument differs from the demonstrative: the latter's middle goes with its extremes necessarily and generates an assent that cannot be doubted, whereas the former's goes with them only probably. Once again, a demonstrative argument can become a dialectical argument if one does not advert to its necessity, for anything that is necessary will be regarded as probable by those who do not grasp the necessity.

An important use of the topic derives from this peculiar characteristic of the probable syllogism. This is that the teaching on the invention of the dialectical middle term can also serve for discovering necessary middle terms—as Aristotle himself notes in his exposition of the *Posterior Analytics* (97a25–28). Thus the treatment of topics is important not only for the dialectician but also for the scientist who is searching for an apodictic proof.

There are various ways of classifying topics, as can be seen from Aristotle's extensive listings of them in his *Topics* and *Sophistical Refutations*. A systematization of them that was influential in the early modern period and was probably known to Galileo is that proposed by Boethius in his *De topicis differentiis*. According to this, the major division is into intrinsic topics, those taken from the matter being disputed about, and extrinsic topics, those taken from extraneous considerations. Intrinsic topics are drawn from three sources: either from the thing concerning which the argument is sought, or from something connected with that thing, or from something separated from it. In the first group are topics of definition, description, and etymology; in the second are topics of parts and wholes, causes and effects, and antecedents and consequents; and in the third are topics of similars and dissimilars, greaters and lessers, and opposites and repugnants. Extrinsic topics may be divided similarly, but their defining characteristic is that they provide arguments from authority, for authority is by its nature extrinsic to the subject matter under consideration.

Here we are interested only in those topics that have a notable affinity with scientific argument. In the first group, the topic of definition is most important; in the second, the topics of cause-effect and antecedent-consequent; and in the third, the topics of similarity-dissimilarity and greater-lesser degrees.[10] We begin with the second group as being closest to the type of argument employed by modern scientists. In addition, after treating the three groups, we consider a notion that Aristotle assimilated to the topic, namely, the problem, which has assumed importance in recent literature on the philosophy of science.

Cause and Effect. Topics relating to causes and effects are important because of the ways causes can be used dialectically when they are not grasped sufficiently to construct strict demonstrations from them.[11] Some would equate a syllogism containing a causal middle with a demonstration, on the basis that demonstrations are always made through causes. While this is true, for demonstrations do use causes, it is also true that not every causal explanation is demonstrative. Yet it frequently happens that a dialectical use of causal argument will prepare for, and ultimately lead to, a strict demonstration. This is seen in the demonstrative *regressus* of the Paduan Aristotelians, to be explained in the following chapter (Sec. 8.6).

Causes are usually divided into the four types discussed in Chap. 1, namely, material, formal, efficient, and final. Different maxims and examples apply to each type of cause, as seen first for material and formal causes. In general, from the positing of a material cause one may deduce that the effect is possible: if there are wood, stone, and cement, there can be a building. Removing the matter, on the other hand, negates the ef-

10. We focus on these because they were among the topics explained in the logic course from which Galileo appropriated materials and which he seems to have employed frequently in his inventive logic. See my *Galileo's Logic of Discovery and Proof*, pp. 123–128.

11. This would correspond to Hume's way of conceptualizing causes and effects, and thus serves to explain why the use of causation always involves dialectical reasoning.

fect: if no fissionable material, then no nuclear weapon. Thus the maxims: when a material cause is posited an effect can be posited; when matter is taken away, so is the effect. Similar maxims apply to the formal cause: if the form is posited, so is the entity of which it is the form, along with its properties and attributes; if the form is removed, so is everything that accompanies it; if a formal effect is posited, so is the form; if a formal effect is removed, the form itself is also removed.

Efficient causes may be subdivided into the necessary and the sufficient, and these give rise to additional maxims or commonplaces. From a necessary and solitary cause one may argue both by affirming and by denying: the earth is interposed between the sun and the moon, therefore an eclipse; the earth is not interposed, therefore no eclipse. Thus the commonplace: when a necessary and solitary cause is posited or removed, so is the effect; and when the effect of such a cause is posited or removed, so is the cause. In the case of a sufficient cause, one may argue from the cause only by affirming and from its effect only by denying: he took poison, therefore he died; he did not die, therefore he did not take poison. The maxim: when a sufficient cause is posited, so is the effect; when the effect is removed, so is the cause.

In addition to these specific maxims, others of a more general nature can be formulated.[12] One of these effectively amounts to a definition of cause: a cause is that which, being present, the effect is there, and being removed, the effect is taken away. Others include the following: cause and effect are correlatives, thus a positive effect must have a positive cause; a particular effect, a particular cause; a universal effect, a universal cause. Similarly, for any one effect there is only one true and primary cause. These can be combined with the topic of greater-lesser degree to formulate a principle of concomitant variation: an increase or decrease in the cause produces an increase or decrease in the effect; an increase or decrease in the effect indicates an increase or decrease in the cause. And this, in turn, can be combined with the topic of similarity-dissimilarity to arrive at a principle of causal proportionality, which invokes the commonplace that similar causes have similar effects.[13] Thus, if A is the cause of B, and C is similar to A and D similar to B, one may argue that

12. Those cited here were frequently invoked by Galileo, as explained in our "The Problem of Causality in Galileo's Science," *Review of Metaphysics* 36 (1983), pp. 607–632.

13. How Galileo formulated and made use of this principle is explained in detail by Donald W. Mertz, "On Galileo's Method of Causal Proportionality," *Studies in History and Philosophy of Science* 11 (1980), pp. 229–242.

C is the cause of D. As used in scientific investigation, the A-B relationship would be one that can be contrived by an experimenter and then used to investigate the similar C-D relationship found in nature.[14]

Antecedents and Consequents. In this topic, "antecedent" is taken to mean anything that necessarily precedes the subject under consideration and the consequent anything that necessarily follows it. Thus, to inquire whether or not a woman has borne a child one may investigate what necessarily precedes birth and follows after it, and these will provide topics from which one can construct arguments pro and con. As with causes, antecedents and consequents may be divided into various kinds: some are connected absolutely, others are connected convertibly or reciprocally, and yet others are connected only *ex suppositione* or suppositionally. With the first kind, the case of absolute connection, the maxims are the following: placing the antecedent necessarily involves placing the consequent; and removing the consequent necessarily involves removing the antecedent. With the second kind, where antecedents and consequents are reciprocating, one may additionally go from the denial of the antecedent to the denial of the consequent and from the placing of the consequent to the placing of the antecedent. The third kind is a special type, where the antecedent precedes the consequent in the order of time and where the consequent necessarily results only on the supposition that something else is posited, the way the blossoming of fruit comes before its eating and the foundation of a building before its walls. In this type the maxims are different: removing the antecedent involves removing the consequent; and placing the consequent involves placing the antecedent.

One can readily see that the logic behind these topics is essentially that of the valid modes of the hypothetical syllogism, the *modus ponens* and the *modus tollens*, which regulate hypothetico-deductive reasoning

14. Two instances of Galileo's use of this principle of causal proportionality are the barge analogy to duplicate tidal phenomena in the seas and the ship's mast experiment to duplicate the fall of objects from a high tower. In the barge analogy, since variations in a barge's motion produce waves in the barge, variations in the earth's motion could produce tides on its surface, and thus the existence of tides would be an indication that the earth moves. In the ship's mast experiment, since an object dropped from the top of a ship's mast falls at the mast's base whether the ship is moving or at rest, the fact that objects dropped from a tower on earth fall at the tower's foot cannot be used to prove that the earth is moving, for even if the earth were moving the falling objects would still impact at the tower's foot.

and its associated procedures of verification and falsification. Our examination of these and related modes (Secs. 7.2 and 7.3) thus confirms that arguments formulated in terms of antecedent and consequent are, generally speaking, not apodictic. Frequently they are topical or dialectical, and as such assist in the process of invention. They aid in discovering the truth, not for actually demonstrating it.

Definition and Similarity. Just as the topic of antecedent-consequent can assist in arriving at a demonstration, so the topic of definition outlines a questioning process that assists in arriving at a definition. The topic suggests procedures for putting a predicate or attribute with a subject and testing it in various ways, both affirmatively and negatively. The affirmative part attempts to define both the attribute and the subject and to determine whether or not they go together in the following combinations: the definition of the attribute with the subject, the definition of the subject with the attribute, and the definition of the attribute with the definition of the subject. The negative procedure is similar, except that one takes the negations or the contraries of the various subjects and attributes and their definitions and tests the same combinations. If this does not yield a satisfactory result, then one resorts to related topics, such as those of differentia, description, and property. That is, in place of definitions of the subject and the attribute one takes differentia associated with them and tries similar combinations. Or, alternatively, one takes descriptions of them and tests the various combinations again. Or, once more, one takes various properties and characteristics associated with them and does the same. In this way one eventually is able to arrive at some type of definition of the subject, even if this is merely descriptive and not essential. The basic maxims that guide these procedures are the following: anything of which the definition (or differentia, description, or characteristic) can or cannot be said applies also to the thing defined (or differentiated, described, or characterized); and whatever can or cannot be said of the definition (or differentia, description, or characteristic) applies also to the thing defined (or differentiated, described, or characterized).

From this general technique, it is possible to branch out into a whole series of comparative procedures, such as considering similars and dissimilars, greaters and lessers and equals, opposites, repugnants, and so on. Similarity is particularly fruitful in that it opens up the search to include analogies and proportionalities that frequently help in the defining process. In this context similars are taken to mean any qualities, quantities, or natures that have elements in common or can be placed in some type of proportional relationship.[15]

Problems, Paradigms, and Programs. Closely allied to the Aristotelian concept of the topic is that of the problem (Gr. *problēma*, taken over directly into the Lat. *problema*), which means a question proposed for solution, an enigma or a riddle or a puzzle. In the context of the *Posterior Analytics* (89b23–25) there are only four types of scientific questions that can be raised, namely, Is it? *(an sit)*, What is it? *(quid sit)*, What are its attributes? *(quia)*, and Why has it these attributes? *(propter quid)*. In the *Topics* (104b1–18) problems are more restricted in scope and are usually concerned with only one of these types, questions of fact *(quia)*. For their resolution one then would be expected to resort to the topics, the exposition of which takes up the remaining eight books of the *Topics*, using techniques and maxims similar to those explained earlier in this section.

Whereas topics are not discussed explicitly by philosophers of science, problems in fact are. In particular, in his *Progress and Its Problems* (1977),[16] Larry Laudan has made this term central to his analysis of scientific progress. For him all of science is essentially problem-solving activity, which he divides into two types, the first concerned with empirical problems and the second with conceptual problems. The former are basically factual, since facts, for Laudan as for Aristotle, are what generate problems for scientists; the second are higher-level difficulties that arise when theories or methodologies are used to explain these facts, whether real or alleged. In this understanding the unit of scientific progress is the solved empirical problem. Therefore the aim of science is to maximize the scope of solved empirical problems, while at the same time minimizing the scope of conceptual problems and of empirical problems that remain unsolved or anomalous. How scientists achieve this goal is examined at length by Laudan, using mainly histor-

15. Galileo seems to have made good use of this topic in his dispute with Christopher Scheiner over sunspots. Scheiner had maintained the spots were actually stars (*stelle*) and thus were remote from the sun's surface. Galileo saw them as resembling nothing more than clouds (*nugole*), and provided detailed descriptions of how sunspots change in size and appearance, and then how clouds do the same. This led him to conclude that the spots were not actually *on* the sun's surface, though they were in some way contiguous with it. See *Galileo's Logic of Discovery and Proof*, pp. 207–211.

16. Berkeley: University of California Press. For a sketch of Laudan's views see Losee, *Historical Introduction*, pp. 233–235.

ical examples. His answer is that they do so by recourse to "research traditions," an expression similar to Kuhn's "paradigms" and imitative of Lakatos's "research programs" (Sec. 6.5). We need not examine here the subtle relationships between these expressions. All three have enough in common with the title of an Aristotelian work variously known as the *Mechanical Problems* or the *Mechanical Questions* to bear comparison with it.

The latter work, also known by the Latin title *Quaestiones mechanicae*, was attributed to Aristotle in Galileo's time, when it had but recently been translated from the Greek. It is now known to have been composed in the Lyceum in the generation after Aristotle's death. Its importance derives from the fact that Galileo's early *Mechanica* took its inspiration from this work, which combined physical and mathematical reasoning in an attempt to find answers to practical questions relating to the movement of weights and heavy objects. On this account it is generally regarded as the forerunner of the modern sciences of rational mechanics and mechanical engineering.

A sampling of the problems posed in the *Mechanical Problems* is the following:

Why are large balances more accurate than small ones?
Why does a missile travel further from a sling than from the hand?
Why are pieces of timber weaker the longer they are?
Why is it easier to move something already moving than something stationary?
Why do objects thrown stop travelling?[17]

The last question is particularly interesting because of the possible explanations that were entertained by the author:

Is it when the force that propelled them is exhausted? Or because of the resistance? Or because of the weight, if any of these is stronger than the propelling force? Or is it ridiculous to deal with these difficulties, when we do not possess the underlying principle?[18]

The admission in the last sentence here is of special importance, for it indicates that within the Lyceum when this work was written, around 300 B.C., no pretense was made of having a true science of moving bod-

17. These problems are selected from the English translation, *Mechanical Problems*, in the Loeb Classical Library edition of Aristotle, *Minor Works*, trans. W. S. Hett, Cambridge, Mass.: Harvard University Press, 1936, pp. 331–407.

18. Ibid., p. 407

ies. Only much later, even after Galileo, would the prospect for such a science be seen, in the work of Isaac Newton and his successors.

When principles are unavailable for the solution of problems, one is forced to make use of dialectical reasoning and seek answers that have some degree of verisimilitude. Undoubtedly a recognition of the feasibility of this procedure has been a factor in the growth of science from its earliest beginnings among the Greeks. Problem-solving has also been a favored technique for the teaching of science since that time. But it was not until Thomas Kuhn that it came to be regarded as an essential feature of science, one that could be used to discern when revolutionary changes had taken place in its various branches. And Kuhn inspired Lakatos, and both in turn inspired Laudan, all of whom in their different ways tie problem-solving or puzzle-solving to making progress in science.

One could make the case that Kuhn, in conceiving the notion of paradigm, has in effect introduced a new *topos* into science, one that would irreversibly confirm the status of modern science as only a special type of probable knowledge. The way in which a paradigm is learned or acquired helps identify the type of topic it might be. It is an extrinsic topic, quite unlike the intrinsic topics that have been discussed earlier in this section. And the common note that serves to identify extrinsic topics is that of authority. In the case of the paradigm the authority is the scientific community, which specifies the procedures to be adopted for working out an acceptable solution to the problem proposed. Investigators operating under a paradigm are in no position to make a certain judgment on the validity of their solution or its ontological implications. They are constrained by communitarian canons, not by the reality they are investigating. Small wonder, therefore, that Kuhn effectively rules out truth and a "full, objective, true account of nature" as the ultimate goal of science.[19]

Much the same evaluation might be given of Imre Lakatos's research programs, at least to the extent that these participate in the character of Kuhnian paradigms. The difference here is that Lakatos, following Popper, recognizes the restraints that reality places on investigations made within the parameters of a particular program, and this provides some assurance that degrees of verisimilitude will increase as the program progresses. But why a researcher follows one program rather than another still seems to be determined by authority, and on that account research programs function only as an extrinsic topic, just as do paradigms.

19. *The Structure of Scientific Revolutions*, 2d ed., Chicago: University of Chicago Press, 1970, pp. 170–171.

On this matter Laudan's research traditions, his counterpart to Kuhn's paradigms and Lakatos's research programs, fare little better. Indeed, Laudan's proposal for the evaluation of competing methodologies on the basis of "standard cases" selected by the "scientific elite" of the day explicitly invokes authority for the solution of the problems that interest him.[20] Thus his proposal would seem to be as authoritarian as the others, and justifies locating all of these proposals within the category of extrinsic topics.[21]

Seen in this way the essential contribution of the Kuhn-Lakatos-Laudan development within the philosophy of science is that this development supplies maxims very similar to those sketched above for intrinsic topics such as cause-effect and antecedent-consequent. It also suggests methods for evaluating lines of inquiry within science that might ultimately result in a definitive scientific contribution. Such lines are regarded by their proponents as falling into two groups, "progressive" or "degenerative," depending on whether they seem to be moving toward or receding from that goal. And this seems to represent a worthwhile contribution. But then an important question still remains. Who is interested in maxims of this type? Hardly scientists, who generally are not given to global considerations and are constrained by their subject matter to go wherever their findings lead. Apparently philosophers of science, and perhaps even historians of science, although both groups seem concerned mainly with specific case studies rather than with evaluating overall trends. Yet there is a final group to be heard from, the sociologists of science. It seems that they find this development of special interest, for it furnishes a novel and striking way of showing the relevance of their discipline to the study of modern science.

7.9 The Social Construction of Science

As noted at the beginning of Sec. 7.6, rhetoric, the art or science of persuasive reasoning, is closely allied to dialectics. Within the Aristotelian tradition the difference between the two is that dialectics is concerned with the probable *(probabile)* whereas rhetoric is concerned with the persuasible *(persuasibile)*. People are persuaded by logical probabilities, to the extent that they understand them, but they are also per-

20. See *Progress and Its Problems*, pp. 155–170; Losee, *Historical Introduction*, pp. 256–258.

21. Laudan's focusing on the scientific elite, however, has the advantage that it explicitly invokes *endoxa* and thus eases the transition from probable to demonstrative reasoning, as explained in Sec. 7.7 above.

suaded, and perhaps more readily, by other types of appeal, such as those to the emotions and to the character of the one persuading. For Aristotle both of these appeals are made through topics, though the appeals are made differently, as he explains first in the *Topics* and then in the *Rhetoric*, which he says is the counterpart *(antistrophos)* of dialectics (1354a1). Dialectics makes use of the syllogism and induction, whereas rhetoric makes use of the enthymeme and the example. Dialectical topics also have a greater range than rhetorical topics, since persuasibles always involve probabilities, whereas not all probabilities are persuasibles. And finally, dialectics is a general faculty for treating questions pertaining to any field of knowledge, whereas rhetoric is more restricted in its appeal, being more appropriate for addressing social and political issues. Within the Aristotelian corpus the "art of rhetoric" is generally seen as an adjunct to the *Politics*, where it can supply the techniques required to convince a group of people or a community to accept a position and then act on it one way or another.[22]

Considering the emphasis placed by Kuhn and the others on the scientific community, the locus where paradigms and programs and research traditions are to be found, it is not surprising that sooner or later attention would be focused on the social dimension of science and the way social factors influence the acceptance of beliefs among scientists. An early focus was on the ways scientists use "rhetoric" when presenting the results of their research—not in the Aristotelian sense of rhetoric, but in the modern political sense of using deceptive language or illustrations to dress up their data and thus gloss over its shortcomings. This would surely be a case where science was being "socially constructed," obviously to its great disadvantage. But then a more serious concern began to manifest itself. Is not knowledge basically a social phenomenon, and should not the sociology of knowledge be employed to cast light on the problems of scientific change? This, one might say, is the most recent development in the philosophy of science. In a way it pulls another support from under the traditional view that science is a perfect type of knowing that reaches necessary conclusions. Not only is science now at best probable, but its probability is affected by factors thus far unthought of, factors that have nothing to do with the reason and objectivity hitherto seen as essential attributes of the scientific enterprise.

One way of handling this "sociological turn" in the philosophy of sci-

22. This view of the relation between dialectics and rhetoric is that of Antonio Riccobono, who taught rhetoric at Padua while Galileo was teaching there; for details, see *Galileo's Logic of Discovery and Proof*, pp. 128–129.

ence, as it has been called, is to invoke a distinction long recognized among historians, that, namely, between "internal history of science" and "external history of science." Internal history studies the development of science in terms of its concepts, laws, theories, and methodologies, and thus it is intelligible only to those who have at least a basic grasp of physics, chemistry, biology, etc., depending on the field whose development they are studying. External history studies the institutions and associations, the social, political, and intellectual ambiences in which science has developed at different places and historical periods, using historiographical techniques that are known to all historians, whatever their specialization might be. It is commonly recognized, of course, that one cannot do history of science without doing both internal and external history. But it is in the latter aspect that the focus will be on matters that interest the sociologist and the political scientist, whereas in the former it will be on matters of interest to the logician and the philosopher.

This proposal is not enough for advocates of the "strong program" in the sociology of science such as David Bloor. In his *Knowledge and Social Images* (1976), Bloor argues that the sociology of knowledge is not restricted to external factors. He makes the stronger claim that the cognitive order is itself causally reducible to the social order. Knowledge is nothing more than whatever informed groups take it to be, what a cognitive community collectively endorses by social consensus. What this involves, he says, is ultimately being impartial with respect to truth and falsity: true beliefs are produced in precisely the same way as are false beliefs. In a later study, *Wittgenstein: A Social Theory of Knowledge* (1983), Bloor takes up the Wittgensteinian theme of "language games" wherein speaking a language is part of an activity, a "form of life" that is open to empirical investigation. Here language becomes for him an interactive tool among communities of speakers, ever changing with the dynamics of social and political interests. And science itself becomes a natural and social activity that generates language games driven more by communitarian interests than by cognitive aims.[23]

Bloor's uncompromising relativism, which makes scientific knowledge simply a reflection of power relations within society and so rejects its rationality and objectivity, has found few advocates. But some aspects of it have been pursued by other writers. Steven Shapin and Simon

23. For the citation of texts and their analysis, see J. E. McGuire's "Scientific Change: Perspectives and Proposals," in Salmon et al., *Introduction to the Philosophy of Science*, pp. 160–164.

Schaffer, in their *Leviathan and the Air Pump* (1985), take up the theme of the scientific enterprise being a form of life in the sense of an integrated "pattern of activity." Just as, for Thomas Hobbes, *Leviathan* or the state is an artifact or a construct that explains human activity, so for Robert Boyle the air pump (and, more particularly, his laboratory) is an artifact or a construct that produces scientific knowledge. "It is ourselves and not reality that is responsible for what we know," they write. "Knowledge, as much as the state, is the product of human actions."[24] Thus, for them, the experimentally produced fact is a social construct. From an analysis of how science functions *in* society they then pass quickly to the conclusion that science is made *by* society. This is a big jump indeed, yet they use it effectively to tie the rise of modern science to the rise of a new social order in the seventeenth century.

Along similar lines are the arguments developed by Bruno Latour and Steven Woolgar in their *Laboratory Life: The Construction of Scientific Facts* (1986). In this they attempt to generalize the theme of social constructivism. In their view scientific facts do not come from nature pure and unalloyed; they are *all* socially constructed. Just as earlier thinkers had made the claim that all facts are "theory laden," so Latour and Woolgar pursue the claim that all facts are "sociologically laden." And just as Kuhn had argued that science is so presented that all traces of its having a history have been removed, so they propose that scientific facts are so constructed that all traces of the construction have likewise disappeared. In the initial stages of investigation persuasion and rhetoric may well be involved, but when community agreement has been reached, results are quickly accorded "fact-like" status. Within the discipline the fact takes on a life of its own and the procedures used to construct it henceforth become invisible.

In *Laboratory Life*, Latour and Woolgar further attempt to develop an anthropology of science, studying what went on in the Salk laboratory from the viewpoint of "anthropological observers." Practices in the laboratory became extended texts that for them were "linguistic practices"; artifacts and instruments similarly became for them "inscription devices."[25] In this way they graphically presented the recent problem of how researchers, and particularly medical researchers, work up and present their findings. Such findings are of great interest to the public, and so it is a small step from this type of analysis for the average person to

24. *Leviathan and the Air Pump*, p. 344, cited by McGuire, p. 165.

25. Again see McGuire, "Scientific Change," in Salmon et al., *Introduction to the Philosophy of Science*, pp. 167–173.

see rhetoric, with its various appeals, as an integral part of scientific endeavor. Even scientists who seek funding for research or prepare grant proposals, including those in the physical sciences, can agree that rhetoric easily enters into their science. And if that is true of the physical sciences, the use of rhetoric will be even more discernible in the human sciences, where the practise is said to have become pervasive.[26]

This perhaps suffices for the introduction of rhetoric and the social construction of science within the context of the current devaluation of science's cognitive claims. A fallible and revisable character first came to be attributed to science at the beginning of the twentieth century, when problems posed by quantum and relativity theories led to its logical reconstruction by members of the Vienna Circle and their followers. Then science's historical reconstruction began shortly after mid-century with the work of Thomas Kuhn and those he inspires. And finally its social reconstruction is taking place toward the century's end under the aegis of David Bloor and the Edinburgh School. Each reconstruction has managed to cut into science's epistemic value, into the truth and certitude that were its hallmarks from the seventeenth to the nineteenth century. Can anything now be salvaged for science's knowledge claims, or is probability, and an incalculable probability at that, the best that one can hope for after four centuries of modern science?

26. See *The Rhetoric of the Human Sciences: Language and Argument in Scholarship and Public Affairs*, ed. John S. Nelson, Allan Megill, and Donald N. McCloskey, Madison: The University of Wisconsin Press, 1987. It should be noted, of course, that there are understandings of rhetoric that are quite different from the social constructivist view. The one that most accords with our study is that of Jean Dietz Moss, to be discussed below in Sec. 10.2.

8 The Epistemic Dimension of Science

The current state of the philosophy of science as portrayed in the last two chapters would seem to indicate that somewhere along the line the magnificent enterprise that was fathered by Galileo at the beginning of the seventeenth century has gotten off the track. Precisely what derailed it is not agreed upon among scholars. Apart from those of the twentieth century, the philosophers who have been most studied are David Hume and Immanuel Kant. Both turn out to be unfortunate choices in matters epistemological, the first for his skepticism with regard to a science of nature, the second for his agnosticism with regard to metaphysics. With such mentors it is not surprising that probabilism and fallibilism have become dominant themes in literature on the philosophy of science. What is unexpected is the new consensus in the movement and the resurgence of interest in realism—precisely the philosophical option rejected by both Hume and Kant. In this chapter we propose to advance the cause of realism by reformulating Galileo's "logic of discovery and proof" in ways that show its relevance to the twentieth-century problematic. The best way to do so is to resume the study of the logic of scientific explanation begun in the previous chapter, concentrating now on material or content logic rather than on the formal logic that has been the main focus heretofore.

From our previous discussion of scientific reasoning it should be clear that there are important differences between hypothetico-deductive (HD) reasoning in the modern sense and demonstrative reasoning in the classical or Aristotelian sense. The principal difference is that HD reasoning is based on a logic of propositions, whereas demonstrative reasoning is based on a logic of terms. A logic of propositions enables one to judge whether inferences between propositions are made correctly or not, but it does not provide canons for judging the truth of the propositions that enter into the inferential process itself. The reason for this is that it does not articulate propositions into the terms or concepts of which they are composed, and so it does not permit one to examine the connection that might be seen to exist between them. As explained in the previous chapter, to achieve *epistēmē* or epistemic knowledge one must be able to discern necessary connections between terms.

The necessary connections that figure most importantly in scientific reasoning are causal connections, that is, those that exist between a cause and its effect. These are of two types: the first reasons from an effect to its proper cause and is known as *a posteriori* reasoning; the second reasons from a cause to its effect and is known as *a priori* reasoning. Since a simple demonstration involves three terms or concepts, S, P, and M (Sec. 7.8), in the first type the M term is an effect and leads to knowledge of a cause, which is expressed in the P term. In the second type the M term is a cause and leads to knowledge of an effect, likewise expressed in the P term. Causes and effects are of various kinds also, and this further expands the possibilities for discerning causal connections and thus for arriving at science in the epistemic sense.

8.1 Causal Connections

The importance of causal explanation for this study, as has been mentioned above, lies in the fact that in many cases it enables one to convert an "if . . . , then . . ." type of reasoning to an "if, . . . and only if . . . , then . . ." type. How this may be done in modern science is most easily seen in instances where quantitative predicates are associated with physical subjects, as occurs, for example, in mathematical physics. Because natural bodies are quantified, it is possible to use their dimensive aspects to set up processes of measurement and so generate metrical concepts. It is further possible to use these dimensive aspects to study quantitative modalities, that, as effects, will lead to knowledge of their proper causes.

The conversion process may be illustrated with a simple example, that of the earth's shape—one of the earth's features not directly perceptible in sense experience but discoverable through scientific reasoning. The reasoning process will be detailed first using the HD methodology of modern science to argue that the earth is probably a sphere. Then the same materials will be reformulated using the canons of Aristotelian or demonstrative methodology to propose the same conclusion as apodictic or certain.

The HD formulation of the argument may be expressed in form (7) of Sec. 7.3 as follows:

> *If p, then* q_1, q_2, q_3*; and* q_1, q_2, q_3*;*
> *therefore* probably *p*

The various propositions that make up the argument may then be fitted into this form as follows:

> ***If*** (*p*) the earth is a sphere,
> ***then*** (q_1) certain observations, such as a ship's mast receding on the horizon, various constellations being seen from only parts of the earth's surface, and precise geodetic measurements, will reveal that they are made from a convex spherical surface; and (q_2) the earth will cast a circular shadow on the moon during lunar eclipses; and (q_3) bodies will gravitate perpendicularly to the earth over its entire surface;
> ***and*** (q_1) these observations *do* reveal that they are made from a convex spherical surface, and (q_2) the earth *does* cast a circular shadow on the moon during lunar eclipses, and (q_3) bodies *do* gravitate perpendicularly to the earth over its entire surface;
> ***therefore***, (*p*) the earth is *probably* a sphere.

Stated in this form, the evidence cited for the earth's sphericity cannot conclude apodictically or with certitude for reasons explained in the previous chapter (Sec. 7.3). The basic limitation here comes from the form of reasoning, which, as the argument is formulated, shows only that a spherical shape as stated in *p* is sufficient to account for the various phenomena listed in the *q*'s. It does not eliminate other explanations, however, and so leaves the mind open to consider other possibilities.

Now we must disengage the content of the foregoing arguments from the HD form and rearrange it in the form of a demonstrative syllogism. One cannot do this with every HD argument; indeed, it seems universally agreed that the vast majority of arguments based on scientific research yield at best probable conclusions. But, should the subject matter of a particular argument permit one to reach a conclusion with certitude, then it should be possible to recast that argument in the form of a demonstrative syllogism. This would seem to be the case for arguments in favor of the earth's sphericity.

Written in the logic of terms rather than that of propositions, a demonstrative syllogism takes the form: "All M is P; all S is M; therefore all S is P." Usually the "all's" are understood, so one can say simply: "M is P; S is M; therefore S is P." Moreover, to avoid having to write each S, M, and P twice, one can say simply "S is M is P," with the understanding that the expression is to be read in three steps. The first begins with the M and reads "M is P"; the second begins with the S and reads "S is M"; and the third begins with the S but skips the M, and so reads "S is P." Because in our argument there are actually three middle terms, the M in what follows is broken down into the three components M_1, M_2, and M_3. Thus the argument proceeds along three parallel lines, "M_1 is P," "S is M_1," therefore "S is P"; "M_2 is P," . . . ; and so on.

Expressed in abbreviated form, therefore, the argument reads as follows:

S	**M_1**	**P**
The earth is	a body from which terrestrial and celestial observations reveal that they are made from a convex spherical surface; and	
	M_2	
	a body that casts a circular shadow on the moon during a lunar eclipse; and	
	M_3	
	a body to which falling bodies gravitate perpendicularly over the entire surface;	
		is a sphere

Here M_1 states an observational effect of the earth's sphericity, which, when worked out in detail using principles of projective geometry, reveal that the observations have been made from a convex spherical surface. M_2 similarly gives an observational effect, though one discernible only at the time of a lunar eclipse. Should such eclipses be seen from all parts of the earth's surface, however, and should one have previously demonstrated that the moon is a sphere, and further be able to calculate the curve that results when the outline of one sphere is projected on another, one should be able to discern that the earth is everywhere rounded and thus is a sphere also. Finally, M_3 states an effect that likewise requires extensive observation. If one knows, however, that bodies fall toward a center of gravity, that everywhere on earth bodies fall perpendicularly to the surface, and that there is one and only one solid figure on whose surface heavy bodies when falling will always be incident at right angles, one can conclude with certitude that the earth is a sphere.[1]

Note here that all three effects are formal effects of the earth's dimensive quantity and thus that the demonstration is made through the exercise of formal causality. They permit one to apply a geometrical predicate to a physical subject and thus to employ a mixture of mathematical and physical reasoning. Obviously they do not entail that the earth is a perfect sphere in a geometrical sense, but only that it is spherical or ball-shaped like a natural object such as an orange, for sense observation alone shows that there are mountains and valleys on the earth's surface. Again, in this understanding of the earth's sphericity no judgment is being made about other geometrical shapes that may more closely approximate the earth's shape, such as its being an oblate spheroid, should one have additional observational evidence that supports this more precise conclusion.

Note also that the schematic form of the above arguments disguises the fact that they all employ suppositions and thus presuppose background knowledge on the part of those to whom they are proposed. The opening sentence of Aristotle's *Posterior Analytics*, in which he sets out what he means by demonstration, makes this clear: "All teaching and all learning through discourse proceed from previous knowledge" (71a1). Those who do not understand projective geometry, for example, or those who are not convinced that, in the circumstances proposed, light travels in straight lines, cannot be expected to give assent; for them the arguments will be merely probable, as noted in Sec. 7.7. Again, despite their being stated in capsule form, the various middle terms summarize knowledge acquired over long periods of time, by many diligent observers, over all parts of the earth's surface. In a case such as this, verifying middle terms is not an armchair activity, one in which a snap judgment is made on the basis of limited personal experience and a few moments' consideration.

Taking these observations into account, if the arguments stated above are valid, one can return to the HD way of presenting them as outlined above and see that there is actually a convertibility in the connection between the *p*'s and the *q*'s. For one who understands the subject matter with which these propositions are concerned, from the viewpoint of for-

1. Arguments of this type go back to the early Greeks, although they have been vastly perfected in the intervening centuries. The first two middle terms, M_1 and M_2, are based on optical principles, whereas the third, M_3, is based on natural or physical principles. Already in the thirteenth century, Thomas Aquinas differentiated between the two types of proof. He did so at the outset of his *Summa theologiae*, First Part, question 1, article 1, reply to the first objection.

mal logic to say "if p, then q" in this context is equivalent to saying "if q, then p." Such being the case, "if p, then q," again in this subject matter, becomes equivalent to "if, and only if, p, then q." That is to say, if and only if the earth is a sphere will a proper causal explanation be given of the various observational phenomena described in the aforementioned arguments. But stating the arguments in the logic of propositions rather than in the logic of terms unfortunately has the effect of blocking out such causal connections. Only when terms such as the S, M's, and P above have been identified can one reflect on their status as causes or effects. So, in a matter such as this, to maintain that scientific reasoning has to be exclusively of the HD type would be to deprive science of epistemic value and unnecessarily restrict its knowledge-gathering capacity. This is not to deny all value to HD methodology, for it is probably the most important dialectical instrument available to the modern scientist. The point is that it is *only* dialectical and not demonstrative. Its exclusive and restrictive use thus makes all of science probable and fallible, and so eliminates the possibility of its ever attaining certitude.

8.2 Definitions

Causes serve an important role as explanatory factors in science, but they are no less important for their role in definition or in the defining process. The defining process is a mental operation whereby one clarifies the meaning of a term by analyzing and relating the elements involved in it. The definition is the result or product of that process, namely, an expression explaining the use of the term or its meaning. Definition is closely related to another mental operation called division, which separates out the various elements involved in the meaning of a term or in the thing it signifies. The ability to discern differences and so differentiate between aspects or elements in the objects of experience is basic to the defining process.

Definition is usually associated with the first act of the mind, that of conceptualization, as explained above in Secs. 4.5 through 4.8. As used in science, however, definitions also make use of the second and third acts of the mind, judgment and reasoning, as further detailed in Sec. 4.9. Definitions can be said to grow or expand as one judges and reasons about the objects under consideration and continues to relate the knowledge thus acquired to what was previously known about them. On this account it is desirable to differentiate the definition itself from the term or the object defined, the *definitum*, or the object to be defined, the *definiendum*. Using this terminology, one can say that strictly speaking a definition is not a sentence or a proposition, but an expression that merely juxtaposes the definition with the *definitum* or *definiendum*. For this reason definitions should not be regarded as true or false, but as good or bad, or adequate or inadequate. This also explains why definitions are said to pertain to the first act of the mind. Although the other two acts are helpful for gathering the information on which the definition is based, the fixing of the meaning of a term or its referent is basically a task of conceptualizing. Such conceptualiztion takes place at each and every stage of an evolving process as one attempts to arrive at definitions that are more and more complete.

Types of Definition. There are two major groupings of definitions. The first group includes all expressions that explain the use of a term; these are called nominal definitions (from the Lat. *nomen*, meaning name, or, in grammar, noun) because the definition is a term usually in the noun form. Nominal definitions are of three types. (1) The first makes use of a synonym or a corresponding word in another language. This is of value only when the alternate term is better known than the *definitum*. (2) The second employs the etymology or derivation of the term from its historical antecedents, or, alternatively, the history of the term's usage in different periods and by various authors. (3) The third is most closely associated with usage in the sciences and is called a stipulated definition. This assigns, by stipulation or by convention and common agreement, a special meaning to be given to a term, which may be a newly-coined verbal or symbolic expression or an old term henceforth to be used in a specific technical sense. A subclass of the stipulated definition is the operational definition, which specifies a method of measurement or a series of operations that serve to give a precise (usually quantitative) understanding of the term's employment (Sec. 6.4).

The second major group of definitions includes all expressions that tell "what" (Lat. *quid*) the *definitum* is and thus explain the meaning of the term and the concept (or intelligible content) the term signifies. This kind of definition is often called a real definition, not because the nominal definition is fictional, but because the *definitum* of the second group refers directly to the thing (Lat. *res*) and not merely to how the term is actually used or henceforth to be employed. The two main types of real definition are the essential definition and the descriptive definition. The elements of an essential definition are the causes that make the thing be what it is, the factors that make its nature or essence intelligible, that is, transparent to the intellect (see Sec. 4.8). A descriptive definition, on the other hand, is based on the object's properties or accidents. Since properties and accidents are more readily grasped by the senses, and since the intellect depends on the senses for its grasp of the object's nature or essence, descriptive definitions are usually the first type acquired. From them one can proceed by comparing, judging, and reasoning, using the *topoi* explained in Sec. 7.7, to arrive at an essential definition.

Defining Factors. Causes have been referred to above as "explanatory factors," and this serves to characterize their role in a demonstration. In view of the extensive exposition in the *Posterior Analytics* of the ways in which causes should be used in finding definitions, to which a good part of Book 2 of that work is devoted, they may equally be regarded as "defining factors." Why this is so can be seen from a few examples. The material cause identifies the stuff out of which an object is made and somehow remains in it. The parts, or components, or elements that go into its composition are its material cause in this sense. Houses are made of wood and brick and steel; these are the stuff out of which they come into being. To say that a house is made of brick already goes a long way toward defining it. Similarly, to say of water that it is made of hydrogen and oxygen in a particular mode of composition tells pretty well what it is. Enumerating the parts or materials that make up a whole is one of the simplest and most obvious ways of defining it.

Similarly, efficient causes, the agents that bring an object into being or perfect its being in some way, play an important role in the defining process. To identify a painting as a Picasso conveys an excellent idea of what it is; the same could be said of Wedgewood china or a Stradivarius violin. Parents are the efficient causes of their children, so to say of offspring that they are sons or daughters of particular parents tells a lot about who they are. Likewise, every craftsman, artificer, or producer in the arts—whether servile, liberal, or fine—is the agent cause behind the production. The same is true in the order of nature: lightning is the cause of thunder; water expanding when in the crystalline state is the cause of ice on lakes and rivers; overeating can be the cause of obesity; and cardiac arrest the cause of death.

Final causes are in some ways the most difficult to understand and in other ways the most illuminating. The *telos* is the end or goal for the sake of which something exists or is done, or what it is that activates an agent or an activity to achieve an end result. The main difficulty with final causes comes in identifying how they function in nature. It is not easy to say what a fly or a lizard is for, in the sense of identifying some obvious utility associated with its being. But there should be no problem discerning what a fly's egg is for, since if properly cared for it will produce another fly. Even more obvious is the *telos* of a fly-swatter, or of any other artifact, for that matter. Whatever a particular device may be, whether for household, industrial, or military use, its nature becomes obvious as soon as one discovers, or is told, what it is for. In a somewhat similar way, many natural processes can be understood in terms of the phenomena with which they end. Examples would be the production of a rainbow or an aurora borealis, or the generation of a new substance in a chemistry laboratory. End results such as these are what come to be best known about the processes and what stimulate investigators to search for the various other causes involved in their production.

While helpful in the work of defining, extrinsic causes such as agent and end are not central to it. The formal cause, on the other hand, is basically the key to an essential definition. Form is the correlative of matter or stuff and so gives meaning to formal causality. Just as material causality focuses on ingredients or parts or components, so formal causality focuses on the figure or shape the ingredients assume, on the whole that gives unity to its various parts. As pointed out earlier, the Latin term *forma*, and its associated term *species*, mean simply shape or appearance. The outline of an object, even the silhouette of a cat or a cow, provides a better idea of what the object is than a detailed analysis of its various parts. For this reason the form tends to be identified with the nature or essence of the object; it tells the kind under which the individual should be subsumed. To define a form or species one must usually have recourse to a larger class under which it is included, called the genus (Lat. *genus*), and the distinguishing traits or differences (Lat. *differentiae*) that serve to separate it from others in the class. Although one might hope to be able to identify a single fundamental characteristic that serves as a *differentia*—as in the definition of man as rational animal (Lat. *animal rationale*), where "animal" is the genus and "rational" the difference—this is not possible generally throughout the entire order of nature. To classify natural species one must employ a group of associated traits that can serve to differentiate a particular type from others in its genus or class. Following this course, taxonomists have proved remarkably successful in finding unique complexes of characteristics that serve to identify the genera and species under which various individual bodies of the inorganic, plant, and animal kingdoms can be located.

The Form of Cat. Earlier in this volume the points were made that the substantial form of a natural body is the primary determinant of the nature of the body and that this is grasped by anyone who is able correctly to identify its substance by name. That is to say, the youth who recognizes a cat and is able to say "That is a cat" has already grasped the nature of cat in a general and confused way. This does not mean that he can define cat precisely and unambiguously. Nonetheless, his conceptualization of cat provides a primary base of reference against which, as he gains knowledge of cat, he can determine its genus and then apply various *differentiae* and so define, or delimit, the class of objects to which the term properly applies. Such a definition would be that of cat as a natural species. This need not imply that the kind has always existed; it could well be one that has evolved over a long period of time. In this understanding, the expression "natural species" simply designates populations or collections of individuals with typical and unique morphology, physiology, and ecology, but subsisting for durations of perhaps hundreds of thousands or even millions of years.

To pursue this method of defining the domestic cat one would have to delineate the fundamental properties that mark off the kingdom, the phyla, the orders, the classes, the families, the genera, and the species under which that organism would be located by a taxonomist. This could be a lengthy undertaking, but the following is suggestive of the procedure that might be followed. First, one may locate the cat's genus and species by reasoning thus:

The domestic cat is an animal of GENUS *Felis*:
- with power of self-development (vs. non-living things: minerals)
- with power of sensation (vs. plants)
- with many-celled structure (vs. animals like the amoeba)
- with a digestive tract (vs. animals like the sponge)
- with a spinal cord (vs. animals like the lancet)
- with jaws (vs. animals like the lamprey)
- with four appendages (vs. animals like the fish)
- with fetal membranes (vs. animals like the frog)
- with warm blood (vs. animals like the lizard)
- with hair and mammaries (vs. animals like the bird)
- with young born outside a material pouch ready to live (vs. animals like the kangaroo)
- with claws (vs. animals with nails like man, or whales)
- with a flesh diet (vs. plant eating, hoofed animals like the cow)
- with teeth highly specialized for flesh-eating (vs. animals like the dog)
- and with retractile claws (vs. animals like the civet and hyena).

and of SPECIES *Felis ocreata*:
- of small size limited to small prey
- basically the Egyptian wild cat, of which the domestic cat is a variant.[2]

2. Adapted from Raymond J. Nogar, *The Wisdom of Evolution*, New York and Toronto: The New American Library, 1963, p. 268.

The foregoing series of disjunctive comparisons serves to separate out the genus of cat *(Felis)*, which includes among its members lions, tigers, leopards, pumas, lynxes, and the domestic cat. The last named differs from others in the genus mainly in its small size and its being limited to small prey. This characteristic identifies the species, as noted at the bottom of the list; it is first found in the Egyptian wild cat, of which the domestic cat is a variant. A more detailed description of the genus and the natural species under which individual domestic cats are contained might then be the following:

> The domestic cat, of which there are numerous varieties differing chiefly in coloration, is a typical member of its genus except that it is small in size and adapted to preying on small animals. The genus is made of animals which are the most highly developed of all flesh-eaters. They have slender, extremely flexible and muscular bodies adapted to crouching and leaping on their prey. The skeleton is light, well built and compact. Each forelimb has five toes, but the thumb of the anterior limbs does not reach the ground. The five toes of each forefoot and four toes of each hind foot are equipped with strong, hooked claws that can be retracted (in all cats but the cheetah) so that the animal can move quickly on thick pads, or extended for striking and tearing its prey.
>
> The skull is relatively short and the facial portion much shortened and rather round in outline. There is a crest to the skull for the attachment of the powerful muscles of the lower jaw. The teeth are very highly adapted for flesh-eating and the tongue is covered with small recurved prickles with which the animal can clean the bones of its victims. The salivary glands are small, the stomach is a simple cylinder and the intestines very short, so that the food which is not masticated passes rapidly through the digestive apparatus. The animal has rich fur usually striped or spotted. Its eyes are acute with a long vertical pupil. It hunts alone, frequently at night, stalking its prey and leaping upon it. The domestic cat is a hunter mainly of mice and small rodents found in or around human residences. Normally it is quiet and self-sufficient in its behavior and clean in its habits. It emits a distinctive cry, the meow, from which its presence is easily recognized.[3]

Notice how, in both the above characterizations, the form of the cat genus is arrived at through a careful study of the cat's parts and organs (material causes, what the cat is made of) and their various functions (final causes, what the parts are for). This seems to be typical of the defining process for the organic realm. Much of the difficulty in that realm arises from the vast chain of agents (efficient causes), acting through the evolutionary process over long periods of time, that produced the popu-

3. Ibid., pp. 269–270, adapted.

lations of organisms we now recognize as natural species. That such natural species exist seems undeniable, and the more information we have about them and how they can be differentiated from similar groupings, the more we know what they are (formal causes, how to specify their natures or essences). It is not necessary to identify cosmic agents in detail, or know how such agents acted in the past, to recognize the populations in which they result. Nor does one have to know all the species to which the domestic cat is related, and the ways in which it may be differentiated from them, to be able to grasp its nature in a general way. Anyone who has experience with cats and discourses about them intelligently has already grasped the universal sufficiently to be said to know the cat's nature.

Defining the Inorganic. Natural bodies in the realm of the inorganic do not present as much difficulty as do living things, for although they may have been formed at different periods of cosmogenesis, they do not "evolve" in the same sense as do members of the plant and animal kingdoms. The chemical elements, for example, can be defined clearly and unambiguously in terms of their location in the periodic table. Classifications of the elements are based on their electronic and nuclear parts (material causes), whose structures or figurations (formal causes) can be grasped in a distinctive way through the use of modeling techniques, as explained above in Chap. 2. A typical definition of any element, as found, for example, in the *Handbook of Chemistry and Physics*, B5–43, will give its name and etymology, the particulars of its atomic weight and atomic number (thus situating it in the periodic table), and then its various physical properties.[4] It additionally gives details of when and by whom the element was discovered, where and how the element is found in nature and in what abundance (thus implying cosmic agents), the various forms it assumes (additional aspects of formal causality), and how it can be obtained from naturally occuring compounds, say, through the use of reagents to produce it in pure form (again, efficient causes). Finally it enumerates various uses and applications of the element and its compounds (extrinsic final causes), and its possible effects on the human organism.

Isotopes of the elements are so numerous that their identifying characteristics have to be given in a separate table (*Handbook*, B233–454). Chemical compounds, both inorganic and organic, can be defined in similar fashion; these likewise require extensive listings of physical properties or constants. For inorganic compounds these are given in the

4. References here and hereafter to the *Handbook* are made to the 66th edition, 1985–1986.

Handbook, at B67–161, and for organic, at C42–553; additionally, structural diagrams or formulas for organic compounds (yet more formal causes) require further illustration, shown at C554–602.

All of this information obviously bears on essential definitions in the world of nature, for it enables one to ascertain the causal factors that make a natural object be what it is. The remaining type of real definition is the descriptive definition, which, as already noted, defines an object in terms of proper or common accidents that in most cases are sufficient to identify it. A mammal, for example, is an animal that suckles its young. Here an operation that can be readily sensed serves as the defining factor. In the animal kingdom, an audible sign frequently supplies the desired description: the meow of the cat, the neigh of the horse, the croak of the frog, the roar of the lion, the laugh of the human. Descriptive definitions based on properties such as these are adequate for most practical purposes. They might be called the first step on the road to an essential definition.

8.3 Demonstrations

Demonstration (Gr. *apodeixis*, Lat. *demonstratio*) is a term first introduced by Aristotle in the *Posterior Analytics* to designate a proof or argument that is concerned with a necessary subject matter and that is true and certain. It is the means whereby one attains the perfect type of knowing he termed science (Gr. *epistēmē*, Lat. *scientia*). Aristotle equates this type of knowledge with causal reasoning when he states: "We suppose ourselves to possess unqualified scientific knowledge of a thing . . . when we think that we know the cause on which the fact depends, as the cause of that fact and of no other, and further, that the fact could not be other than it is" (71b8–11). He likewise makes an explicit connection between science and demonstration when he goes on: "By demonstration I mean a syllogism productive of scientific knowledge, a syllogism, that is, the grasp of which is *eo ipso* such knowledge" (71b17–19). And finally, to explain how demonstration can serve as an instrument of scientific knowing, Aristotle defines it in terms of the requirements such knowing places on its premises: "The premises of demonstrated knowledge must be true, primary, immediate, better known than and prior to the conclusion, which is further related to them as effect to cause" (71b20–22).[5]

5. How all of these expressions are to be understood is a subject of dispute among commentators on Aristotle's text. In view of Galileo's importance as one of the

The premises referred to here are the two propositions symbolized in Sec. 8.1 as "M is P" and "S is M," which when joined together as the antecedent of the argument entail the conclusion "S is P" as a necessary consequent. These premises must be known to be "true," since probable or doubtful or false premises cannot support a true and certain conclusion. The premises must be "primary" in the sense that they do not themselves require demonstration and so may be seen as indemonstrable. If the premises function as part of a series of demonstrations, this allows that the conclusion of one may serve as a premise of the following demonstration, but that all must ultimately be reducible to "first" premises that are not themselves demonstrated. Premises of this type are also called "immediate" because no middle term or intermediary is needed to join their subjects with their predicates. In such a case, the intellect makes the connection directly from the meanings of the terms, when, for example, it joins the *definitum* or *definiendum* with an essential definition, once this has been grasped by induction from sense experience. The premises will then be "better known than" the conclusion, since they are known on their own terms whereas the conclusion is not, it being made known through the premises, and "prior" to the conclusion, since they are known "before" the conclusion, for if assent is not given to them there is no basis for assenting to the conclusion. The premises then "cause" the conclusion as an "effect," and this in two ways: as causes of one's knowledge of the conclusion, or as the instrument wherewith the mind infers the truth of the conclusion from previously known truths; and as causes, in an ontological sense, of the attribute or property that is predicated of the subject in the conclusion.

Types of Demonstration. Demonstrations may be divided into two broad types: direct or ostensive demonstrations, which prove a true conclusion from true premises, and indirect or negative demonstrations, which prove that a conclusion is impossible, and thus not true, by reducing it to another impossibility or absurdity that is more known. The second type is most effective when it is proposed along with, and as part of, a manifest dichotomy or disjunction. In this case the elimination of the alternative(s) requires one to accept a conclusion as true, but only indirectly, without having proper reasons in its support. Reductions to the

founders of modern science, in what follows we give the interpretation found in the logic course he appropriated from the teaching notes of Paulus Vallius, S.J., around 1589. Here the *Treatise on Demonstration* is of particular importance. For details, see my *Galileo's Logical Treatises*, pp. 125–215, and *Galileo's Logic of Discovery and Proof*, pp. 134–190.

impossible are frequently used in mathematical proofs, and they were employed with great ingenuity by Archimedes, and then by Galileo, who successfully extended their use into the realm of mathematical physics.[6]

An ostensive demonstration is had whenever a statement is given together with the reason for its truth, that is, whenever the question "why" is answered. Because there are different senses of "why," there are different kinds of direct demonstration. And since the reason "why" is expressed in the middle term of the demonstrative syllogism, this means that the various types of demonstration correspond to the kinds of middle (M) that link the subject (S) and the predicate (P) of a scientific conclusion. Thus, for Aristotle, the general division of ostensive demonstration is into two types, each with a distinctive kind of middle term: these result either in knowledge of the fact (Gr. ὅτι, Lat. *quia*) or in knowledge of the reasoned fact (Gr. διότι, Lat. *propter quid*). Only demonstration of the reasoned fact strictly satisfies all of the requirements enumerated by Aristotle at 71b20–22, but demonstration of the fact can be seen to satisfy them with a few qualifications that are introduced and generally accepted by his commentators.

Demonstration of the reasoned fact (*propter quid*) assigns the proper ontological cause of a property's inhering in, and being attributed to, the subject. In the most perfect type of *propter quid* demonstration, all of the terms of the syllogism, S, M, and P, are commensurately universal. However, as long as the middle term and the attribute or predicate are convertible, there is a *propter quid* demonstration, even though the subject of the given demonstration has a more limited extension than the proper subject of the attribute. For example, every isosceles or equilateral triangle has three internal angles equal to two right angles, not because it is isosceles or equilateral (subjects with more and more limited extensions), but because it is a triangle (the subject with the greatest extension). What is essential to a *propter quid* demonstration is that the cause of the attribute be proper, and it is proper to all triangles, whether they be isosceles or equilateral or whatever, to have three internal angles equal to two right angles.

Demonstration of the fact (*quia*) is had whenever the middle term is not the proper cause of the attribute. This demonstration can be causal, and thus *a priori*, when a remote cause is assigned. How this works is most easily seen in the example provided by Aristotle: the negative

6. Examples of how Galileo made use of this type of proof are best found in his early treatises on motion and mechanics. See *Galileo's Logic of Discovery and Proof*, pp. 239–263.

demonstration that a wall does not breathe because it is not living (78b15–27). The proper cause of not breathing, in this case, is not having lungs; many living things do not breathe, and yet the fact of the wall's not being alive is sufficient here to explain its not breathing. A demonstration of the fact can also be *a posteriori*, when the middle term is not a cause at all, but an effect of the attribute. If the effect is not adequate or convertible with the cause, the demonstration yields knowledge of the existence of the cause and some of its conditions. If, however, the cause and effect are of commensurate universality, then the demonstration makes known the proper cause, and hence the terms may without circularity be recast as a *propter quid* demonstration. The process wherein this is done is known as the demonstrative regress, to be explained in Sec. 8.6.

Mixed Sciences. Demonstrations can be made in mixed or middle sciences, and here by the nature of these sciences each of the two premises pertains to a different discipline. In the case of mathematical physics, the major premise will be a mathematical truth pertaining either to the science of number (discrete quantity) or to the science of magnitude (dimensive quantity) and the minor premise will be a truth pertaining to one or other branch of the science of nature. The middle term will pertain to the category of quantity, and since this occurs in both premises, it must be understood differently as it occurs in each. In the major premise the middle will be an abstract quantity, pure quantity as conceived in the imagination, whereas in the minor premise the middle will be a physical quantity, a quantified aspect of a body or phenomenon found in the order of nature. There are obvious differences between the two—for example, the difference between the sphere as studied in spherical geometry and the sphere as instantiated in the shape of an orange or the earth. To bridge this difference one must employ auxiliary principles called suppositions (Gr. *hupotheses*, Lat. *suppositiones*) that are agreed upon by practitioners of the mixed science, in this case mathematical physicists. Alternatively, if common agreement is lacking, the one proposing the demonstration will present them as petitions (*petitiones*), to which assent must be given before the demonstration can be seen or understood.

Changes of meaning in the middle term of a syllogism is closely associated with the problem of analogy and how this may be employed in scientific reasoning. Quantity as understood in physics is analogous to quantity as understood in mathematics, for, granted that the two meanings are partly the same and partly different, there is a proportionate understanding of the two terms that allows transitions to be made between them.The way matter is understood when speaking of protomatter or "first" matter is similarly analogous to the way matter is understood when speaking of composite substances or "second" matter. Within the Aristotelian tradition, a transition of this type has generally been countenanced in demonstrative reasoning. This being so, in the context of modern science it would appear that the use of metrical concepts as middle terms in physico-mathematical demonstrations presents no insurmountable obstacles (Sec. 7.1).

Related to this practice is the question whether theoretical concepts can similarly be employed in such demonstrations. Here an answer may be suggested on the basis of the way theoretical concepts are used to model aspects of reality that are not directly accessible in sense experience, as explained above in Sec. 7.4. If a model gives an analogous insight into a theoretical entity, and especially in cases where the entity is proposed either as a part or component of a natural body or as having a nature in its own right, one need not exclude theoretical entities from use as middle terms in demonstrations, despite the fact that their existence was first investigated using probable or hypothetico-deductive reasoning. Analogous middle terms standing in for theoretical concepts would then be carrying the burden of apodictic proof just as would quantitative middles when standing in for metrical concepts.

Looking back over the various kinds of cause discussed in this chapter, one may inquire which types figure most frequently in the explanations provided by the mixed sciences. The question is important because of the extensive discussions of causality that are found in philosophy of science literature. When the term "cause" is used there, invariably the meaning intended is efficient cause. (If a Humean interpretation is given, in the sense of causation as explained above in Sec. 7.5, this is efficient causality without causal efficacy and so is not causality as here being discussed.) One might gain the impression from this that most of the demonstrations in modern science are offered in terms of efficient causality. Surprisingly, this is not the case. Because of the preference for quantitative explanations, most demonstrations in science invoke formal causality of various types, although these frequently presuppose the action of some efficient cause, as will be seen in Sec. 8.1. This is true of the three middle terms discussed above, all of which are based on dimensive quantity, invoking as they do the various properties of a sphere and yet presupposing the action of causal agents, such as sources of light rays and the force behind gravitational action.

To return now to Aristotle's definition of demonstration, as already noted this can be seen to apply, with suitable qualifications, to demonstration *quia* and to demonstrations in the mixed sciences. The main problem is with the characterization of premises as "first and immediate." In the case of a remote cause, granted that the premises are not actually first and immediate, if the proof can further be resolved to a proper cause, then the premises are virtually first and immediate in light of that additional resolution, and this suffices to qualify it as a scientific proof. Similarly, if the proof requires a mathematical premise that is presupposed as demonstrated in, say, geometry, this is like an immediate proposition in physics, for there is no middle term in the latter discipline through which it can be demonstrated. Thus, on the basis of the supposition, the proof qualifies as scientific. Another difficulty arises when demonstrating the existence of a cause from an effect, in light of the "more known than" and "causes of" clauses in the definition. In the order of nature, causes are more knowable in themselves than are effects, but in human knowing this is not the case, since in sense experience effects are usually more known, or more readily knowable, than are their causes. This also relaxes the requirement for the premises being causes of the conclusion, for then they need not be causes of the being of the effect, but only causes of our knowing it, and this suffices for an *a posteriori* demonstration.

8.4 Foreknowledge and Suppositions

From what has been said to this point, prerequisite knowledge or foreknowledge (Lat. *praecognitio*) has an important role to play in the demonstrative process. Obviously, the truth of the premises must be solidly established. The minor premise contains the term that serves as subject of the conclusion; to this term is predicated the middle term, usually providing a definition of it. Such a premise, in which a definition is predicated of a subject, is self-evident. The major premise in every demonstration connects a cause and an effect, the nature of the demonstration depending on whether the cause or the effect is the middle term. This premise becomes known through a process of induction. This terminates not merely in empirical or statistical correlation, but in an understanding of, or insight into, the nature of cause and effect and their necessary bond, which likewise is self-evident for those who see it.

Some foreknowledge, however, is required of the terms of the demonstrative syllogism. Usually the existence of the subject, or minor term, must be known for attributes to be joined to it. In an *a posteriori* demonstration that establishes the existence of the subject, however, only the nominal meaning of the subject-term can be used. For example, if one wishes to demonstrate the existence of an electron, one must start with the definition of that term, namely, that it means unit electric charge. A definition of the subject is also necessary as the predicate of the minor premise. This definition represents either a cause in *a priori* demonstration, or an effect in *a posteriori* demonstration. In the latter case, as has been said, it is only a nominal definition.

In the reasoning that leads up to a *propter quid* demonstration, some knowledge of the conclusion of the demonstration is already implicit. The existence and the definition of the subject are known, and also the nominal definition of the predicate. The latter may already be known in the asking of the question to be demonstrated, e.g., Why is the sky blue on a cloudless day? The fact of the conclusion may be known by observation, as in the example given. Even a definition of the predicate as an accident may be known, but not a definition of the predicate as a property of the particular subject. The definition of a property as such presupposes knowledge of its necessary connection with its proper subject, and this is precisely what has to be demonstrated. Therefore, the foreknowledge of the predicate as a property can be only a nominal definition. There is no foreknowledge of the middle term as such, since the finding of the middle term is itself the demonstrative process.

The self-evident principles of demonstration are called its premises. They deal with definitions and insight into causal connections, and thus their self-evidence becomes apparent only after a careful and sometimes extended investigation. The principles must be proper for a *propter quid* demonstration. There are other more general self-evident principles involved in demonstration, such as the principle of noncontradiction, the principle of agreement and disagreement, and the logical principles governing the syllogism. These higher principles or axioms are implicit in every demonstration, but they do not function as the content of premises from which conclusions are deduced.

Apart from such self-evident principles, various types of supposition must be counted as part of the foreknowledge required for demonstration in particular sciences. In all of the natural sciences, for example, (1) the implicit supposition is made that an order of nature exists and that this order is unimpeded either by natural causes, e.g., chance occurrences within nature itself, or by unnatural causes such as miraculous events. Similarly, (2) the role of form under the aspect of end implies the supposition of a form that, as the normal termination of a natural process, dictates a suppositional necessity to the matter. This results in a demonstration made *ex suppositione finis*, generally typical of those in the natural sciences (Sec. 1.6). When considerable observation and experimentation are involved in the demonstrative process, it is legitimate (3) to suppose a principle that can be established by induction and experiment, even though those to whom the demonstration is proposed have not yet verified the principle themselves. Akin to this is (4) the supposition of a principle that is capable of *a posteriori* proof or (5) the supposition of a principle that is proved in one part of a science and so is usable without proof in another part of that science. All five of these suppositions were commonly employed in Aristotelian science to the end of the sixteenth century and were known to Galileo.[7]

In demonstrations of mixed or intermediate sciences such as mathematical physics, the most important foreknowledge is found in the suppositions that are employed by common agreement in the science. In mathematical physics these can be of many types. The most basic is (6) the supposition of a mathematical definition or a theorem that is proved in mathematics and is usable without proof when applied to the order of nature. Two further precisions or variations on this are the following: (7) the supposition of a mathematical principle or definition that is posited for computational purposes and is not claimed to be true in nature, and (8) the supposition of a mathematical definition or theorem that is true in mathematics and is claimed to have a valid application in nature. The latter supposition allows for two additional modifications: (9) the supposition of one or more conditions under which a mathematical definition or theorem will be verified in nature to a specified degree of approximation, and (10) the supposition of one or more conditions involving the removal of impediments or of extraneous efficient causes that permit a mathematical definition or theorem to be similarly verified. The sixth and eighth suppositions are typical of the mixed sciences of optics and statics as these developed in classical antiquity and the Middle Ages; the seventh was additionally invoked with some frequency in astronomy before the seventeenth century. The ninth and tenth were im-

7. See my "Aristotle and Galileo: The Uses of *Hupothesis (Suppositio)* in Scientific Reasoning," *Studies in Aristotle*, ed. D. J. O'Meara, Washington, D.C.: The Catholic University of America Press, 1981, pp. 47–77; reprinted as Essay 3 in my *Galileo, the Jesuits and the Medieval Aristotle*, Collected Studies Series CS346, Hampshire (UK): Variorum, 1991.

plicit in the works of Archimedes and explicitly stated and defended by Galileo, particularly in his studies of mechanics and local motion.[8]

8.5 The Demonstrative Regress

Galileo's knowledge of Aristotelian logic is revealed in one of his earliest Latin manuscripts, written probably in 1589, while he was teaching or preparing to teach at the University of Pisa. As already noted, the manuscript contains a treatise on demonstration, *Tractatio de demonstratione*, which was appropriated from a complete course on logic and methodology offered at the Jesuit university in Rome, the Collegio Romano, in the previous year by the Jesuit Paulus Vallius. The last question of the treatise is devoted to the demonstrative regress (Lat. *regressus demonstrativus*), a distinctive methodology that was developed by Aristotelians at the University of Padua in the fifteenth and sixteeenth centuries. Through the intermediary of another Jesuit also teaching in Rome, Ioannes Lorinus, Vallius had appropriated the teaching from the logic text of Jacopo Zabarella, the preeminent philosopher at Padua, who had recently perfected and explained the method.[9]

A peculiar thing about the *regressus* is that the term itself is Latin and has no direct counterpart in Greek; thus it is not found in Aristotle's text. Yet the doctrine is clearly Aristotelian in origin, though it did not assume identifiable form as a scientific methodology until the second century, when it was discussed by Galen in his *Ars medica*. Then it was taken up by Greek commentators on Aristotle in the fourth century, and finally received its fullest treatment by Averroes in the twelfth century. The first Paduan to take up the teaching was Pietro d'Abano, who combined the ideas of Aristotle in the *Posterior Analytics* with those of Galen in the *Ars medica* in an attempt to reconcile disputes that had broken out between the philosophers and the medical doctors at the university. After him a number of philosophers there, including Paul of Venice, Agostino Nifo, Girolamo Balduino, and Bernardino Tomitano, taught the doctrine and elaborated on it in various ways. Tomitano, who was Zabarella's teacher at Padua, made the point that natural science must use a method of discovery, or demonstration *quia*, as the first step in its proofs. He also

8. Ibid.

9. For details of this appropriation, see the introduction to *Galileo's Logical Treatises*, pp. 3–83. More particulars concerning the Latin text of the manuscript are given in Galileo Galilei, *Tractatio de praecognitionibus et praecognitis* and *Tractatio de demonstratione*, ed. W. F. Edwards and W. A. Wallace, Padua: Editrice Antenore, 1988.

identified this first stage as an inductive process, the way of inquiry (*inquisitio*), which would be followed by a second deductive stage, which would employ demonstration *propter quid*.[10]

Zabarella's Regress. Within this general setting, Zabarella went about formulating what was to become the standard method of discovery and proof attributed to the Paduan Aristotelians. A professor at Padua from 1564 to 1589, Zabarella wrote numerous works on logic and natural philosophy, including a treatise on the *regressus* and an extensive commentary on the *Posterior Analytics*. He defined the regress as "a kind of reciprocal demonstration in which, after we have demonstrated the unknown cause through the known effect, we convert the major proposition and demonstrate the same effect through the same cause, so that we know why the effect exists."[11]

For Zabarella, logic is practically identified with method, and science itself is nothing more than logical method put to use. Moreover, all scientific progress from the known to the unknown is either from cause to effect or from effect to cause; the former he calls the demonstrative method, the latter the resolutive. Certain knowledge will not result unless an essential and necessary connection can be discerned between cause and effect. The demonstrative method is most appropriate in mathematics, where causes are more known than their effects, but resolutive method is characteristic of the natural sciences, where one must start from effects because causes are generally unknown. And since one cannot set out from the unknown, in physics one must employ a kind of secondary procedure, the resolutive method that leads to the discovery of principles. Hence for Zabarella the resolutive method is subordinate and the servant of the demonstrative. The end of demonstrative method is perfect science, knowledge of things through their causes; the end of resolutive method is discovery (*inventio*) rather than science, since by resolution one seeks causes from their effects so that one may afterwards know the effects through their causes, not rest in a knowledge of the causes themselves.

Having thus set the stage for his discussion of resolutive method, Zabarella points out that there are actually two methods of resolution.

10. A detailed account of this development, abbreviated in what follows, will be found in W. A. Wallace, "Circularity and the Paduan *Regressus*: From Pietro d'Abano to Galileo Galilei," *Vivarium* 33/1 (1995), 76–97.

11. *De regressu*, cap. 1, in *Opera logica*, 3d ed., Cologne: Zetzner, 1598, col. 481; this edition has the same pagination as the Frankfurt 1608 edition, both of which have been photographically reproduced, the first by Georg Olms, the second by Minerva.

The one is demonstration from effects, which is efficacious for the discovery of objects that are obscure and hidden. The other is induction (*inductio*), which is a much weaker form of resolution used for the discovery of what is not completely unknown and yet is not clear either. Induction, for Zabarella, is most helpful for the discovery of principles that are known naturally and so do not require proof through something else. Induction does not grasp an object through something else; rather it reveals the object through itself. Within the object the universal is not really distinct from the particular; the two are differentiated there only by the human mind. And since the object is better known to us as a particular than as a universal, induction is a process from and to the object itself. That is, it proceeds from knowing an object in the way it is more obvious to us to knowing it in the way it is more obscure and hidden. On this account, not only are the principles of things known by induction, but also the principles of science and of knowing itself, which are otherwise indemonstrable.[12]

Zabarella's analysis here provides a method of discovery whereby ordinary experience can be brought to the level of the scientific. He explains this process in his treatise on the regress, where he first makes a distinction between two types of knowing, one confused, the other distinct, and which he says applies to both knowledge of the effect and knowledge of the cause. A confused knowledge of something is awareness of its existence without knowing what it is, whereas a distinct knowledge grasps not only the existence but also the nature of the object. With regard to particulars, Zabarella makes the further point that it is not necessary that every fact or particular be recorded, since a general principle can be gotten inductively by a careful examination of selected instances. This procedure, which he calls "demonstrative induction" (*inductio demonstrativa*), is effective only in a necessary subject matter where objects have essential connections with each other. After a certain number of these have been examined, the mind straightaway notices the essential connection, and then, disregarding the remaining particulars, it proceeds at once to bring all the particulars together in the universal.

After the effect-to-cause stage of the regress has been completed, Zabarella notes, a third intermediate "work" (*labor*) must intervene, during which the mind passes from knowing the cause confusedly to grasping it distinctly. Some call this a *negotiatio* of the intellect, as did

12. The material in this and the preceding paragraph is summarized from Zabarella's *De methodis*, *Opera logica*, cols. 134–138, 226–229, 268–271. For fuller details, see "Circularity and the Paduan *Regressus*."

Nifo, but Zabarella prefers to think of it as a mental examination (*examen mentale*) or consideration of the cause that leads to understanding what it is. Two things help in this: one is the knowledge that the cause exists, the other is a comparison of the cause with the effect through which it was discovered. The comparison is made initially without full knowledge that one is the cause and the other the effect, merely to gain information about the conditions (*conditiones*) of each. When the first of the conditions has been discovered this helps in the discovery of another, until finally the cause comes to be recognized as providing the unique explanation of the particular effect.[13]

Zabarella's use of "confused-distinct" to differentiate the two kinds of knowledge of the cause in this intermediate stage has important implications for understanding how a transition can be effected from dialectics to demonstration, as mentioned in the previous chapter (Sec. 7.7). A number of his predecessors at Padua had argued that the first stage of the regress is not apodictic and thus should be regarded not as demonstrative but as merely dialectical. Apparently Zabarella was aware of the texts where Aristotle interprets *endoxa* as a type of *quia* knowledge, that is, knowledge "of the fact" rather than "of the reasoned fact." For Aristotle this type of knowing attains truth that is partial and obscure, another way of saying "confused," but true nonetheless. Thus, as Zabarella sees it, the work of the intellect in the *examen mentale* is to remove the obscurity and confusedness in the initial apprehension of the cause. Then, by the time it is completed, the *examen* will have elevated the first stage of the *regressus* from a conjectural argument to a true demonstration, and the entire process will consist of two reciprocal demonstrations, one *quia* and the other *propter quid*, as in his original description.

Galileo's Appropriation. The explanation of the regress found in Galileo's *Tractatio de demonstratione* follows closely that of Zabarella in his *De regressu*, though there are a few changes of terminology. The main difference is that, where Zabarella speaks of knowing a cause confusedly at first and then distinctly, Galileo distinguishes between knowing it materially at first and then formally. The alternate terminologies can be explained by the way Lorinus first appropriated Zabarella's text and how this appropriation was later emended by Vallius. By tracing

13. This and the preceding paragraph abbreviate Zabarella's explanation of the process in his *De regressu*, in *Opera logica*, cols. 484–487; again see "Circularity and the Paduan *Regressus*" for details.

successive changes from Lorinus to Vallius to Galileo one can ascertain the intended equivalence of the sets of terms, confusedly-distinctly and materially-formally.[14]

As Galileo presents the regress, it involves two demonstrations, one *quia*, a demonstration of the fact, and the other *propter quid,* a demonstration of the reasoned fact. Galileo refers to these demonstrations as progressions and notes that they are separated by an intermediate stage. The first progression argues from effect to cause and the second in the reverse direction, thus "regressing" from cause to effect. For the process to work, the demonstration of the fact must come first, and the effect must initially be more known than the cause, though in the end the two must be seen as convertible. The intermediate stage effects the transition from it to the second demonstration. The transition itself involves time and work, for testing when experimentation is needed and for computation where mathematics is used, so that the causal connection can be made clear and precise. The result is then seen in the second progression, when the cause, having been grasped "formally" or precisely as it *is* the cause, and indeed the unique cause in view of the convertibility condition, is shown to be necessarily connected with the effect. Only at this stage is knowledge that is strictly scientific attained, for then one knows the reasoned fact, the proper cause of the effect that is being investigated. The entire process may be schematized as follows:

First progression: from effect to cause; the cause is materially suspected but not yet recognized formally as the cause.

This generally presupposes that the effect is more known to the senses than the cause and that it awakens interest or curiosity, thus serving as the starting point of the investigation. At the end of this progression the cause comes to be suspected as plausible, i.e., known "materially," that is, as a cause and as really existing, and thus as the terminus of the demonstration of the fact, but known only in a general way and not yet as the unique cause of the effect.

Intermediate stage: the work of the intellect, testing to see if this is a cause convertible with the effect, eliminating other possibilities.

This usually requires a period of time, during which the work is that of the mind, not the senses, although sensible experience plays an important and essential part. The main task is one of testing the causal connection, that is, investigating and eliminating other possiblities, and so coming to see the

14. For an account of how this was done, see my "Randall *Redivivus*: Galileo and the Paduan Aristotelians," *Journal of the History of Ideas*, 49 (1988), pp. 133–149, reprinted as Essay 5 in my *Galileo, the Jesuits and the Medieval Aristotle*.

cause as being required wherever the effect is present. At the end of this period the cause is grasped "formally" by the mind, that is, precisely as it is the cause, and the unique cause, of the particular effect.

Second progression: from the cause, recognized "formally" as the cause, to its proper effects.

At this stage the necessary connection between cause and effect is grasped. The cause is seen as ontologically prior to the effect and thus as more knowable in itself, even though the effect is more apparent to the senses. The cause is also seen to explain the effect, that is, to give a proper reason why the phenomenon appears as it does. On this account the second progression constitutes a demonstration of the reasoned fact.

In Jacopo Zabarella's account of the regress, as has been seen, the intermediate stage of the *examen mentale* is one of considering or comparing. Another way of understanding the *examen*, one consistent with Zabarella's own scientific work, is to see it as a type of testing or probing. This aspect of mental activity is captured by the Lat. *discrimen*, akin to the Lat. *periculum*, which in turn derives from the Gr. πεῖρα, meaning test. Zabarella consistently uses the term *periculum* to describe his tests and experiments, even more than does Galileo, who also uses it to describe his experimental studies to determine the true cause (*vera causa*) of local motion in his early writings on that subject.[15] Moreover, in his commentary on the *Posterior Analytics*, Zabarella indicates the point in that work where Aristotle himself describes the regress. This is in the passages of Bk. 1, ch. 13, where Aristotle explains the reasoning process whereby it is known that the moon is a sphere and that the planets are closer to the earth than the fixed stars (78a31-b12). Both of these conclusions pertain to the mixed science of astronomy, which uses mathematical premises to explain the phenomena of the heavens. On both counts, then, experiment and mathematics, it would seem that the Paduan demonstrative regress was open to innovation on precisely the points that would later be exploited by Galileo.

How the demonstrative regress works in astronomy may be seen from a study of Galileo's treatise on the sphere, the *Trattato della sfera ovvero Cosmografia*, which he composed at Padua around 1602 and used there

15. See Charles Schmitt, "Experience and Experiment: A Comparison of Zabarella's View with Galileo's in *De motu*," *Studies in the Renaissance*, 16 (1969), pp. 80–138, and Luigi Olivieri, "Galileo Galilei e la tradizione aristotelica," *Verifice* 7 (1978), pp. 147–166; also W. A. Wallace, "Galileo's Pisan Studies in Science and Philosophy: A Portent for the Future," forthcoming in *The Cambridge Companion to Galileo*.

to instruct students in Ptolemaic astronomy. The context is his explanation in the *Trattato* of the aspects and phases of the moon and the ways these vary with the moon's synoptic and sidereal periods (GG2:251–253).[16] These phenomena depend only on relative positions within the earth-moon and earth-sun systems and do not require commitment to either geocentrism or heliocentrism, being equally well explained in either. Basic to the explanation is the conviction that these aspects and phases are effects (*effetti*) for which it is possible to assign the cause (*la causa*) [GG2:250]. Among the causes Galileo enumerates are that the moon is spherical in shape, that it is not luminous by nature but receives its light from the sun, and that the orientations of the two with respect to the earth are what cause the various aspects and the places and times of their appearances. The argument follows closely the paradigm provided by Aristotle in *Posterior Analytics* I.13, noted above, to show that the moon is a sphere. It involves one basic supposition, namely, that light travels in straight lines, and this is what governs the intermediate stage. This allows one to use projective geometry to establish the convertibility condition, namely, that *only* external illumination falling on a shape that is approximately spherical will cause the moon to exhibit the phases it does at precise positions and times observable from the earth. The reasoning may be summarized as follows:[17]

First progression: from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.

Effect	**Cause**
the moon's aspects and phases are probably produced by	its spherical shape, illuminated by the sun, at various positions and times

Intermediate stage: the work of the intellect, testing to see if this is a cause convertible with the effect, eliminating other possibilities.

The moon is not luminous by nature, it is externally illuminated by the sun, and it is observed from many different angles; *only* a shape that is spherical and this illumination will cause it, under these circumstances, to exhibit the aspects and phases it does at precise positions and times observable from the earth.

The precise phenomena can be calculated from the **supposition (ex suppositione)** that light travels in straight lines, using theorems proved in projective geometry.

16. The reference here and in what follows is to Antonio Favaro, ed., *Le Opere di Galileo Galilei*, 20 vols. in 21, Florence: G. Barbèra Editrice, 1890–1909, following the standard way of citing Galileo's texts.

17. Adapted from *Galileo's Logic of Discovery and Proof*, pp. 194–197.

Second progression: from the cause, recognized formally as the cause, to its proper effects.

Cause	**Effect**
the moon's spherical shape,	produces the moon's aspects and
illuminated by the sun,	phases, calculated using the
at various positions and times	laws of geometrical optics.

The argument, as can be seen, combines both physical and mathematical reasoning and thus pertains to the mathematical physics of Galileo's day, the middle science of astronomy. For the physical part, note that purely mathematical entities are not being discussed; what is under study is the moon, which is a natural body, whose shape is natural, and whose nature is such that it does not emit light as does the sun but shines by reflected light. For the mathematical part, the properties or aspects being studied in the moon are associated with its dimensive quantity and as such are amenable to treatment using theorems from the science of dimensive quantity, namely, geometry. In the above summary these properties are not stated explicitly, although they make up the bulk of Galileo's exposition in the *Trattato*, for there he spells out in detail how the various phases appear at different times depending on the relative positions of the moon, sun, and earth.

Here the calculations may be skipped over and only the insights that underlie them delineated. These are that the moon itself is a sphere, not a mathematical sphere but a natural body whose shape is closely spherical, and that a spherical shape alone, of all possible geometrical figures, can explain how an externally illuminated body possessing it will manifest phases that are alternately new, crescent, half, gibbous, and full, and then gibbous, half, crescent, and new again, but each time with figures that are laterally reversed from those in the preceding series. The reason for the different appearances at different times and places in the heavens is that the interval between two new moons (the synodic period, that of the earth-moon system) is two days longer than the time required for the moon to return to the same configuration of stars and so to be again in conjunction with the sun (the sidereal period, that of the earth-moon-sun system). Thus the situation is complex and requires a knowledge of projective geometry as well as of lunar and solar movements for its comprehension. The same type of knowledge is required to compute the times of lunar and solar eclipses, and Galileo, interestingly enough, likewise explains these calculations in the *Trattato*.

A number of suppositions are also involved, although only one is stated explicitly in the above schema. This is that light travels in straight lines. Along with this the person considering the argument must either know beforehand, or come to know in considering it, properties of spheres under external illumination as well as characteristics of earth-moon and earth-sun motions known from observational astronomy. Another supposition is that the moon is illuminated by light coming from the sun (the efficient agent involved), a conclusion that requires careful observation to be established. These suppositions pertain in various ways to types 3, 8, and 9 listed in the previous section. For those who have scruples of the type "The sun may not rise tomorrow," it will be necessary to invoke type 1 also, for the demonstration requires that there be an order of nature, unperturbed by miraculous events or chance occurrences such as cosmic catastrophies.

In light of these suppositions, one may say that the demonstration overall is made *ex suppositione*. Yet not until the intermediate stage, when the "work of the intellect" is completed and the one engaged in the regress is assured of the truth of the suppositions, is it possible to entertain the second stage. There, assured of having knowledge "of the fact" with regard to what is involved, one can complete the regress and formulate the demonstration "of the reasoned fact." It is only at this second stage, therefore, that one attains scientific knowledge of lunar phases and not merely opinion concerning them. The requirements for a science in the Aristotelian sense have been met and one is entitled to make apodictic statements about this phenomenon in the heavens. And it is important to note that this superior type of knowledge is acquired only in stages. At the beginning of the regress knowledge of the moon's aspects and phases is in some sense conjectural—a partial and obscure grasping of the truth about them, what Zabarella would call "confused" knowledge of their cause and Galileo, grasping that cause only "materially." By the time the regress is completed the obscurity is gone, the confused has become the distinct, and the cause is grasped "formally," precisely as it is the cause and thus able to provide the basis for scientific knowledge.

8.6 Models and Ontology

With this fuller understanding of demonstration and its requirements we are in a position to consider in more detail a problem touched on toward the end of Sec. 8.3, namely, whether theoretical concepts or terms can serve as middle terms in the demonstrative syllogism. There it was suggested, in light of the role theoretical concepts can play in modeling the real (Sec. 7.4), that they can give an analogous insight into theoretical entities, particularly when these are proposed as parts or components of natures that are observable and so more readily understood. It remains now to investigate how models can function in this way and so lead to the incorporation of new types of entities into the ontology of modern science.

In the way modeling was introduced at the outset of this work (Sec. 1.1), an epistemic model was characterized as having two referents: the first is the object or nature that is more known, from which the model is taken; the other is the object or nature that is less known, to which the model is applied. The more known factor is the origin of the model, the less known, its application. Though many types of model are employed in scientific reasoning, the basic divisions may be characterized in terms of the relationships that hold between the origin and the application.[18]

The simplest kind of model is one in which a more or less exact replica is constructed, but on a smaller or larger scale, in order to study a particular phenomenon. Here the origin and the application are similar in form, or isomorphic, and a size or dimensional change serves mainly to differentiate the two. We shall refer to this type of model as a scale model. It is extensively used in applied sciences such as engineering and architecture,[19] but it also has some uses in pure science, to be explained presently. As opposed to the scale model, the more interesting and fruitful model, one that finds major use in scientific research, is what we shall call the analogue model. In its case the origin and the application are different in form, and thus there is more than a scale change between the two. As a first approximation one may say that the difference between the forms is that the form of the origin pertains to the subject matter of one field of investigation, whereas that of the application pertains to the subject matter of another. A simple example, from applied physics, is the use of electrical circuit analysis to study problems of mechanical vibration. This is analogue modeling because the origin, an electric circuit, is different in form from the application, vibratory motion. The point of similarity is mathematical, namely, that electric current flow and mechanical displacement can be described accurately by the same differential equations. The mathematical forms are similar even though the physical phenomena they describe are different.

18. The exposition that follows has been influenced by Mary B. Hesse, *Models and Analogies in Science*, Notre Dame: University of Notre Dame Press, 1966, and more particularly by Rom Harré, *The Principles of Scientific Thinking*, pp. 33–62.

19. In mechanics it poses the problem of dynamic similarity, the first topic Galileo investigates at the outset of his *Two New Sciences*, namely, why it is that, although the geometry of large and small structures is similar, the materials of which they are constructed seem to make the small structure stronger than the large (GG8:51).

Scale Modeling. As mentioned, scale modeling has been productive of some scientific discoveries. An historical example is the discovery of the first essentially correct explanation of the rainbow by Theodoric of Freiberg in the first decade of the fourteenth century, to be discussed in Sec. 9.1. Whereas most of his predecessors from Aristotle all the way to Roger Bacon regarded the rain cloud as an effective agent in the production of the rainbow, and even saw some similarity between the colors of the bow and the spectrum resulting from the sun's rays as they pass through a quartz crystal or spherical flask filled with of water, they tended to see the crystal or the flask as modeling a spherical cloud or collection of raindrops. Theodoric, on the other hand, was the first to see that a spherule of quartz or a globe of water could be used to model, not a cloud, but an individual raindrop. His experiments with rays of sunlight passing through crystals and flasks enabled him to duplicate in a laboratory situation, and thence to explain, the geometrical properties of the primary and secondary rainbow. He did so in terms of the ways rays of light enter individual raindrops, are refracted at the air-water and water-air interfaces, and also reflected at the interiors of the drops. Only through the use of a "magnified" raindrop was such experimentation possible in his day, and this explains why scale modeling led to the discovery.[20]

Another example of scale modeling would be the explanation of a planetary perturbation in the solar system by means of a putative planet, a hypothetical entity, not yet known to exist. Here the unknown entity is modeled after a known entity, and upon discovery, say, in the case of Neptune, is found to be similar in form to the planet whose motion it was perturbing, namely, Uranus.[21] Sometimes there is an appreciable size difference between the known entity and the unknown, for example, a flask of water and a raindrop, and sometimes there is not, as in the case of Neptune and Uranus. Again, there are times when there will appear to be great differences in size between the model and the thing modeled, which themselves are rectified when the effects of distance on observation are taken into account. Stars, for instance, appear so small that they were first modeled as points of light, but with the advance of scientific knowledge they are now modeled more accurately as suns. The sun is

20. For details, see Rom Harré, *Great Scientific Experiments*, Oxford: Phaidon Press, 1981, pp. 92–100, as well as Sec. 9.1 below.

21. The research process that led to Neptune's discovery was actually quite complex; for a complete account see Morton Grosser, *The Discovery of Neptune*, Cambridge, Mass.: Harvard University Press, 1962.

surely the largest object in any reasonable proximity to us, and compared to it a point of light is as small as one could imagine. Yet, the progress of science has revealed that these points of light are bodies of the same order of magnitude as our sun, so the end result is modeling in the same size range. In fact, we now say that our sun is a star of a certain type, which shows how we tend to model one entity on another, and how the study of one phenomenon leads us to an understanding of others.

Analogue Modeling. In analogue modeling, as already noted, there is a change of form between the model and the thing modeled, and this usually because the model is taken from one field of investigation that seems well understood in an attempt to understand a phenomenon occuring in another that is less so. Studying mechanical vibration problems through electrical circuit analyses is, in this sense, analogue modeling. A better example, one associated with a famous scientific discovery, is William Harvey's classical work on the circulation of the blood, to be analyzed in Sec. 9.4. Here, rather than analyze the flow of blood in mammals as Galen had done on the model of total absorption from a linear flow process, Harvey correctly understood this on the model of a circulatory flow maintained by a mechanical pump. His was analogue modeling in the sense that pumps pertain to mechanics or hydraulics whereas the flow of blood pertains to biology or physiology.[22]

More complex types of analogue modeling construct models that are based on two or more different disciplines in an attempt to understand a baffling or complex phenomenon. A classical example is the attempt to understand phenomena associated with the elementary constituents of matter on the model of a wave-particle. Here the application is in the area of atomic or nuclear physics, whereas the origin is from a twofold source: hydrodynamics or electromagnetic theory for wave aspects, kinematics or dynamics for particle aspects. Another example would be the Bohr atom when this is used as a model to explain the absorption and emission spectra of various gases. In this case the application is in the area of chemistry or spectroscopy, whereas the model itself is again based on two disciplines: classical mechanics for the planetary features of the nucleus-electron system in the atom and radiation theory for the

22. Despite the mechanical model, Harvey was no mechanist but was consistently Aristotelian in his scientific techniques. One of the best accounts of his methodology is that of Herbert Ratner, "William Harvey, M.D.: Modern or Ancient Scientist?" *The Thomist* 24 (1961), pp. 175–208, reprinted in *The Dignity of Science: Studies in the Philosophy of Science presented to William Humbert Kane, O.P.*, ed. J. A. Weisheipl, Washington, D.C.: The Thomist Press, 1961, pp. 39–72.

way in which that system emits and absorbs energy. To these perhaps one might assimilate the model behind Newton's thinking when he formulated his first law of motion. Although he spoke of a body at rest or in motion, what he actually had in mind was a mass-point. A body, strictly speaking, cannot move in a straight line, whereas a mass-point obviously can. In this case the origin of the analogue is again twofold: physics for the mass aspect, geometry for the punctiform aspect that is required at least implicitly for the formulation of the first law.

Both of these types of modeling, but particularly analogue modeling, provide powerful tools for dialectical inquiry and for scientific investigation. It would take us too far afield to canvass such possibilities here, though we have already considered some of them elsewhere.[23] For the present, suffice it to state that epistemological realism, coupling causal analysis with analogical reasoning, can contribute much to an understanding of the cumulative growth of scientific knowledge, along lines to be developed in the final two chapters. The basic thesis is that science is concerned with a study of the real, not with the logical as such, and that real entities can be the subject of true existential predication, that they have natures that can be understood, and that there can be progress in this understanding. Much of this progress comes about through the continued application of modeling techniques, which make new existential claims possible and enable scientists to preserve their generalizations, while modifying them and interpreting them in ways that achieve an ever-deepening understanding. And all of this is done in virtue of the mind's ability to understand effects through their causes, and so to explain phenomena in terms of the ontological antecedents that make them be what they are.

8.7 A Logical Empiricist Ontology

Having begun this chapter by juxtaposing hypothetico-deductive reasoning to demonstrative reasoning in the classical or Aristotelian sense, we turn at this point to consider the different ontologies that result from a consistent application of the two types of reasoning to the data of modern science. Admittedly not all logical empiricists make the same

23. See particularly our "Causality, Analogy, and the Growth of Scientific Knowledge," reprinted in *From a Realist Point of View*, 2d ed., pp. 213–227. Also "The Reality of Elementary Particles," *Proceedings of the American Catholic Philosophical Association* 38 (1964), pp. 154–166, reprinted in the same, pp. 171–183; and "Elementarity and Reality in Particle Physics," *Boston Studies in the Philosophy of Science* 3 (1968), pp. 236–271, reprinted in the same, pp. 185–212.

knowledge claims on the basis of their reasoning, as can be seen from the many disparities in epistemology among philosophers of science. Here we can focus on but one school as fairly representative, that of Willard Van Orman Quine, who explicitly addresses the problem of "what there is" from a logical empiricist point of view. Quine is significant for this study in having brought the notion of "natural kind" once again to the forefront of philosophical discussion.[24] The ontology he proposes thus lends itself readily to being juxtaposed to that here being developed.

In a volume of essays by various authors entitled *On Nature*, Quine has an article, "Sticks and Stones; or, the Ins and Outs of Existence," in which he summarizes his mature views on matters relating to the epistemology of science.[25] Here he begins his account with the statement that the brain is often compared to a computer, then affirms a strong commitment to the empiricist principle *nihil in mente quod non prius in sensu* (nothing in the mind not previously in the senses), and ends by professing "a robust realism."[26] On these three points there would seem to be broad agreement with the ideas developed in Chap. 4 above. His intervening analysis of scientific discourse, however, differs on significant points with the theory of knowledge expounded in that chapter.

The computer model Quine prefers in his austere empiricism is the black box, whose input is waves and particles and whose output is an emission of descriptions. He is not adverse to earlier inputs from parents and teachers, but these are reducible, he says, to sound waves and light from the pages of books. Earlier empiricists thought that sense data were the primary given, but he would substitute for these the triggering of our nerve endings.[27] From such triggering the only way of deciding "what there is," that is, constructing an ontology, is from an analysis of our discourse about the world.[28] Quine proceeds to do this in two stages, the first based on ordinary discourse and yielding the world of common sense, the second based on science and yielding a more complex universe. The system he constructs to account for both his ordinary ontol-

24. See his *Ontological Relativity and Other Essays*, New York: Columbia University Press, 1969, pp. 114–138; this section is reprinted with the title "Natural Kinds" in Boyd, *The Philosophy of Science* , pp. 159–170.

25. L. S. Rounder, ed., *On Nature*, Boston University Studies in Philosophy and Religion, vol. 6. Notre Dame, Ind.: University of Notre Dame Press, 1984, pp. 13–26.

26. These statements will be found on pp. 13, 14, and 23 respectively of the article.

27. Ibid., p. 13

28. See Quine's *From a Logical Point of View*, Cambridge, Mass.: Harvard University Press, 1953, pp. 1–19.

ogy and his scientific ontology is presented schematically in Fig. 8.1; it may serve as a guide to the following summary of his thought.

The verbal processing that leads a child to make objective references is effected mainly by the use of grammar, shown in the column on the extreme right, which implies the ontology that is sampled in the column on the extreme left. From nonverbal stimulations the child is conditioned to say things like "milk" and to indicate assent or dissent with "yes" and "no." Even when these are single words, they are best thought of as sentences, such as "that is milk," "this is a dog," "it's raining."[29] Quine allows that this account works better for substances than for bodies because of the different visual shapes of bodies seen from various angles, but through associations of similarity and succession the child learns to attribute existence to them also: "Fido," "chair," "stick."[30] The child also acquires words for the properties he attributes to substances and to bodies: "white" to "milk," "red" to "chair," and so on.[31]

When these words are employed in sentential contexts, different kinds of sentences result, depending on how the predication is made. For our purposes only two are important: "occasion sentences" and "standing sentences." Examples of the first are "That's milk" and "It's raining"; these are true or false depending on the occasion in which they are used. More important are the second kind, what Quine also calls "observation categoricals," for these are the stuff of which an incipient science is made. Their distinguishing characteristic is that they involve a "whenever" or "wherever" construction and thus convey the impression that they can be true "once for all." Three examples of standing sentences are the following: "When it rains it pours," "Where there's smoke there's fire," and "When it thunders there is lightning." Each of these involves a conditional expectation, that is, an implication, and its truth or falsity can be ascertained only by putting the expected result to empirical test. Should experience show that an anticipated outcome is negated, the sentence does not represent a universal truth. This is the fate of the first two sentences, "When it rains it pours" and "Where there's smoke there's fire." But the third sentence, "When it thunders there is lightning," holds up under repeated testing and so comes to be accepted as true. In this type of sentence, says Quine, "science is in the bud."[32]

29. "Sticks and Stones," p. 15.

30. Quine makes this point in his "What Is It All About?" *The American Scholar* 50 (1980–1981), p. 44.

31. Ibid., p. 48.

32. "Sticks and Stones," pp. 16–17.

A Logical Empiricist Ontology			
First Level **Objective References**		**Second Level** **Verbal Processing**	
Ordinary Ontology Conditional Expectation	**Scientific Ontology** Value of a Variable	**Logic**	**Grammar**
BODIES "Fido" "chair" "stick"	INDIVIDUALS "observable" "unobservable"	TERMS monadic dyadic triadic, etc.	WORDS substantives, modifiers conjunctions relative clauses
SUBSTANCES "milk" "dog" "stone"	PHYSICAL OBJECTS "organism" "electron" "particle" "field"	PROPOSITIONAL OPERATORS negation conjunction implication	SENTENTIAL CONTEXTS subjected predicated
[ATTRIBUTES] "white" "thunder" "lightening"	ABSTRACT OBJECTS "number" "property" "class" "class of a class"	VARIABLES, QUANTIFIERS "for all *x*" "for some *x*" "the *x* such that"	ASSENT, DISSENT "yes, no" "whenever, wherever" "everything" "something"
[NON-EXISTENTS] "Pegasus" "unicorn"	REDUCTIVE INTERPRETATION "progression of classes" "portion of space-time" "mind-body states"	PROXY FUNCTIONS "the *f* of a . . ."	TRANSLATIONS "number" "nombre"
"The inscrutability of reference"			

Fig. 8.1 Quine's Ontology

From the outlines of this extremely truncated account, one can see how Quine builds up the world of ordinary experience. Various implied or negated observation categoricals, expressed in familiar speech, provide the basis for reference to objects, and so we confer on them objective existence. That is sufficient for us to incorporate the referents of the top nine words in the first column on the left of Fig. 8.1 ("Fido," "chair," etc., down to "lightning") into our ontology, and to discard the bottom two, "Pegasus" and "unicorn," as referring to non-existents.[33]

At this point we move to a more scientific ontology, which goes beyond grammar to the formal structures of logic for its verbal processing.

33. Ibid., pp. 18, 25.

Logic has already been involved, albeit implicitly, in structuring the familiar world of experience, for this has been built up through the use of implications, conjunctions, negations, etc. The reasoning on which it is based is that of the hypothetical syllogism: rejection of some entities on the basis of falsification, conditional acceptance of others through verification or corroboration. So, for Quine, our "world" is something like the empirical content of a scientific theory, even though we may not advert to that in ordinary ways of speaking. To approach the problems of scientific language we have to unpack what is already there, to become more formal, as it were. How this is done is shown schematically in the two inner columns of Fig. 8.1, entitled "Logic" and "Scientific Ontology" respectively, reading from right to left. It is here that Quine's trademark appears, for the transition from one column to the other is effected by the application of his famous principle, "To be is to be the value of a variable."[34] This enables him to take account of the scientist's use of mathematics, his reference to unobservables, etc., while at the same time guaranteeing that his science, though always revisable, has substantial empirical content.

The entries in the "Logic" column are drawn from propositional logic and the predicate calculus. These enable us to give accurate expression to ordinary sentences, including those involving relative clauses. For example, when someone says "I visited Alex at his country home," we may think of this as a function *F*, applied to Alex, *a*, or as *Fa*. Our reference to Alex is then but an instantiation of a variable bound in the function *F*, "*x* such that I visited *x* in *x*'s country home." Again, to say "I bought Fido from one who found him" is to employ a more complex function, *Gab*, involving reference to two objects, Fido as *a* and the one who found him, *b*. *G* then reads: "*x* such that I bought *x* from *y* such that *y* found *x*," with *a* instantiating *x* and *b* instantiating *y*. These examples are not foolish; for Quine they represent the key to his ontology. As he puts it, "To posit an object, to recognize it as existing, is to admit it as a value of bound variables." Where ordinary language is concerned, this is to admit it as the reference to a relative pronoun. When we abstract the relative clause, "one whom I visited at his country home," from our first sentence about visiting Alex, writes Quine, "we thereby recognize Alex as an element of our ontology."[35]

Up to this point Quine has been discussing physical objects: Alex and Fido, stick and stone. What about the properties or classes we attribute

34. *From a Logical Point of View*, p. 15.
35. "Sticks and Stones," pp. 19–21.

to them, when, for example, instead of saying "That's a dog" we say "Fido is a dog" or "Dog is a species"? Sticking to his principle, Quine says that here the question is simply whether or not to admit property terms and class terms in the position of a bound variable. If we do admit them, that is, if from "Dog is a species" we make the existential generalization to "For some *x*, there exists an *x* such that *x* is a species," then we posit "species" as part of our ontology also. The only difference between class terms and those designating individuals is that the former, i.e., properties and classes, are abstract objects, not physical objects. Quine realizes that this move opens the door to a "lavish positing of gratuitous and dubious entities." His reply: "This is all very well; ontology is not the everyday game." Ordinary people may not do so, but scientists and philosophers "put their theories over into ontologically clearer form" and thus end up with a more sophisticated universe.[36]

One of the most important instances of abstract objects figuring as values of bound variables, continues Quine, is the case of numbers. Quantitative laws are central to serious science, and so we must have some way of importing quantities into our ontology. The obvious way to do this is to use the route just indicated, that by way of classes:

> The glories of number, in the service of science, are further to the glories of classes; for it is known that numbers of all kinds—integers, ratios, reals, imaginaries—can be reconstructed as classes within set theory, where the ontology comprises just individuals of some sort, and classes of them, and classes of those classes, and so on. Other objects of classical mathematics—functions, relations—can be reconstructed as well. This hierarchy of classes, with concrete individuals of appropriate sorts at the bottom, evidently suffices for all of science. It is all there need be said to be.[37]

With one sweep Quine has here picked up the entire world of mathematics and dropped it into that of nature and of natural science. No problem now for the mathematical physicists: they are on a par with the naturalists and the humanists in their investigations of "all there is."

But that still leaves open the problem of individuals. The discussion thus far has been of observable individuals and the properties attributed to them in our macroscopic ontology. Does Quine have anything to say about individuals that may be unobservable, the hosts of entities inhabiting the microcosm and the megacosm opened up by recent science? Predictably, he does. "Many philosophers," he writes, "view the two sorts of objects as fundamentally unlike, these being observed and those

36. Ibid., pp. 21–22.

37. Ibid. p. 22.

being invented or conjectured."[38] He does not agree. Observable entities and unobservable entities are on an equal par. There is as much ground for objective reference to electrons and fields, to quarks and black holes, as there is for the sticks and stones of our parochial universe.

Finally, to conclude the exposition of Quine, there is the problem of bridging the various languages with which we now have to deal, the ordinary and the scientific, the individual and the abstract. Quine proposes to do this by a one-to-one mapping technique used by mathematicians to move from one domain to another. For this he uses what he calls a "proxy function," shown at the bottom of the third column from the left on Fig. 8.1 as "the *f* of a . . . ," and to be read as "the *f* of a dog," "the *f* of a prime number," etc.[39] The technique is similar to that of translation when we move, say, from one modern language to another.

Two examples may suffice. An individual physical object, such as Fido or a stick, may be considered as essentially the material content of a place-time, the portion of space-time each occupies. Taking the proxy function *f* to read "the place of," we can then replace every instance of "*x* is a P" (as in "*x* is a stick") with "*x* is the place time of a stick." When we do this, nothing really has changed; we are merely interpreting our sense impressions differently, and we now have a handy way of replacing sticks with atoms, elementary particles with fields, and so on.[40]

The second example builds on this first. We may go further and replace space-time regions with a different proxy function, one using quadruples of numbers (say, *x*, *y*, *z*, *t*) or any arbitrary system. When we do this we leave space-time for the world of pure set theory. In this domain "there are no longer any physical objects to serve as individuals. . ., but there is no harm in that."[41] Our exercises are those of reductive interpretation; nothing has changed, we are merely interpreting our empirical data differently. In justification of his proxy function, Quine explains that it

> is not to be seen as casting doubt on sticks, stones, and the rest, but as having to do with the theory of evidence. . . . It tells us that the evidence on which we base our theory of sticks, stones, electrons, and the rest would equally well sustain a theory whose objects were other things altogether. But the evidence is none the worse for that.[42]

This explains, of course, why Quine can compliment himself on his

38. Ibid., p. 23.
39. Ibid., p. 23.
40. "What Is It All About?" p. 51.
41. Ibid., p. 52.
42. "Sticks and Stones," p. 25.

"robust realism." His ontology is indeed very full: it encompasses all of the objective referents in the languages of the mathematician and the physicist as well as in that of the man on the street. But there is a high price to pay for all this, which Quine himself concedes when he speaks of "the inscrutability of reference,"[43] shown across the bottom of the first two columns on the left of Fig. 8.1. He recognizes that to ask what objects a person is talking about is to ask how we propose to translate his terms into ours. What then turns out to be of overriding importance is the structure of discourse, not the choice of its objects. "The objects serve as mere nodes in the structure, and this is true of the sticks and the stones no less than the electrons, quarks, numbers, and classes."[44] So Quine admits, in the last analysis, that he sees "all objects as theoretical."[45] Science really has only one thing to go on: its discourse, its sentences,

> true sentences, we hope; truths about nature. The objects, or values of variables, are just reference points along the way, and we may permute them or supplant them as we please as long as the sentence-to-sentence structure is preserved.[46]

Perhaps it is not doing Quine a disservice to sum up this thought by rephrasing his famous predecessor Bertrand Russell, who once described mathematics as "the science in which we never know what we are talking about nor whether what we say is true."[47] For Quine, it seems, when we talk about objects, we likewise are never sure of what we are talking about, but we may still claim that what we are saying is true. But, being the mathematical logician that Quine is, the truth to which he refers is probably not that of correspondence with reality that has been proposed above (Sec. 4.9), but rather that of coherence or consistency, the type of truth with which logicians are habitually concerned.

8.8 The Two Ontologies Compared

Obviously there is much to criticize in Quine's ontology,[48] but whatever its strengths and weaknesses there can be no doubt that it offers a stark contrast to the ontology presented throughout this work. In Quine's writings the primacy is accorded to logic, not only in natural science but

43. "What Is It All About?" p. 53.
44. "Sticks and Stones," p. 24.
45. "What Is It All About?" p. 53.
46. Ibid., p. 54.
47. In his "Recent Work on the Principles of Mathematics," *The International Monthly* 4 (1901), p. 84.
48. For a detailed critique see John C. Cahalan, *Causal Realism*, Lanham-New York-London: University Press of America, 1985.

in all discourse whatever. Thus far in our development, no objection has been raised to anyone's being logical in discourse; indeed, the logic of the *Posterior Analytics* has been constantly urged as a foundation for the scientific enterprise. But at this point, objection must be voiced to Quine's putting logic first, and formal logic at that, before acknowledging that one must be aware of a subject matter to be logical about. In natural science, primacy must be accorded, not to logic, but to nature. And by and large those working in the natural and human sciences (and ordinary people too) do know what they are talking about, although they may not be always sure that what they are saying is true.

To restate our main thesis: the natural sciences are concerned with the world of nature, with the many entities that make up the world in which we live; and the human sciences are concerned with human beings, men and women like ourselves, whom we know very well before we enter the domain of logic. Scientists study objects like Fido, and the stick, and the stone; they study sulphur and lead and Mars, and fish and dugongs and human beings as well. When they engage in discourse about these things they are very much aware of the objects of their discourse. Nor are they content to consider these merely as existents; they want to know what they are, they inquire into their natures as well. That, of course, requires logic. It requires them to move into a second level of discourse, where they reflect on what they already know and consider not real entities but logical entities, that is, the second intentions they form to regulate first their expression (grammar) and then their thought (logic). So they arrive at the requirements for valid HD reasoning, of which Quine is so well aware. But that is not enough. They must go beyond the requirements for logical form to consider requirements that arise from the thought content and not merely from the sentential or propositional form in which that content may be expressed. It is in this arena that they concern themselves with the canons for defining and demonstrating that were set out in the earlier sections of this chapter. And so they encounter the perennial problem posed by Aristotle: how to go from the more known to the less known; how, in modern terms, to go from the macroscopic domain, from the familiar world of ordinary experience to the strange world of quarks and pulsars, genes and genetic codes. Some of the things they encounter are seen as subsistent entities that perhaps have natures of their own; others are thought of as components of more observable things that better explain, or can be used to model, their natures. It is in this way that scientists grasp the nature of radium, for example, when they model that nature in terms of its nuclear and electronic structure and from this explain the many radioactive and chemical properties of that particular element.

Despite the limitations of Quine's ontology, there are points of similarity between it as portrayed in Fig. 8.1 and the typology of concepts set out first in Fig. 4.4 and then, in fuller form, in Fig. 7.1. The most striking is Quine's partitioning his ontology into two basic levels, the first that of "objective reference," the second that of "verbal processing"; these partitions directly correspond to those of "real concepts" and "logical concepts" shown in Figs. 4.4 and 7.1. The main difference lies in the number of columns in the respective elaborations, five in Fig. 7.1 as opposed to the four in Fig. 8.1. What is left out by Quine is the "Perceptual Order," the first column on the left of Fig. 7.1. He does not start with a perceived extramental reality but instead relies on the "input" presupposed to his system, "waves and particles" and "the triggering of our nerve endings." (This, of course, is a strange empiricism, for it puts him right away in the realm of theory, from which he can never quite extricate himself.) Otherwise there are counterparts in the remaining four columns. The last two columns on the right of Fig. 8.1 ("Logic" and Grammar") are represented in the single columns on the right of Figs. 4.4 and 7.1 ("Logical Concepts"), the first showing both grammatical and logical terms, the second, only representative expressions from propositional logic. Quine's "Ordinary Ontology" is duplicated in the "Real Concepts, Physical" of Fig. 4.4 and the "Physical Concepts, Observable" of Fig. 7.1. His "Scientific Ontology," on the other hand, is found partitioned out somewhat differently. The "unobservables" of Fig. 8.1 are located among the "Physical Concepts, Theoretical" of Fig. 7.1 and its "abstract objects" among the "Mathematical Concepts" at the bottom of Fig. 7.1. Its "nonexistents" are also situated among the "Physical Concepts, Theoretical," only there they are indicated with a right-pointing arrow (→) as in "mermaid→" to show that they do not really belong among physical concepts but are basically logical constructs. There are no counterparts for the "reductive interpretation" and "proxy functions" boxes of Fig. 8.1, nor does "the inscrutability of reference" have a special place, although it does apply to the theoretical terms shown with left-pointing as well as right-pointing arrows, as in the "←wave-particle→" and "←space-time→" terms among the "Physical Concepts, Theoretical" of Fig. 7.1.

To conclude, just as one might ask, in light of Quine's starting point, what is empirical about logical empiricism, so when he has finished his ontology one might inquire what is logical about it. And the simple answer is, practically everything, certainly far more than the ontology reflected in Figs. 4.4 and 7.1. The key factor is Quine's "inscrutability of reference," for although his so-called first level refers to some objective reality, his referent here is actually a question mark, something vague enough to include "bodies," "substances," and "Pegasus" as well as abstract objects such as "number," "class," and "class of a class." In other words, the first-level entries of Fig. 8.1 have the earmarks of logical universals, despite their including such very real entities as "Fido," sticks, and stones. For Quine, all are "inside the mind," to use the terminology of Chap. 4, but their extramental reality is left ultimately in doubt. That is why, for him, "observables" and "unobservables" are on an equal par. He sees "all objects as theoretical," and so their ontological status can pose no problem.

This may all be very well for a mathematical logician working in the tradition of Bertrand Russell. But our concern is not with mathematical logic but with nature and how it is known in the natural sciences. Here, being able to differentiate between observables and unobservables, and among the latter, theoretical entities, is a matter of utmost importance. So it turns out that discussion in abstract terms is not enough when constructing an ontology. It is necessary to consider concrete cases, to see how knowledge of nature is first acquired, then gradually perfected in various fields of investigation. The final two chapters of this study are therefore devoted to a detailed explanation of how the cumulative growth of knowledge has actually taken place in the sciences. In Chap. 9 representative studies of scientific growth are provided in areas as diverse as optics, astronomy, mechanics, chemistry, and biochemistry. Chap. 10 then examines controversies that have arisen over the epistemic value of these contributions and details how the respective controversies have finally been resolved—to the lasting benefit of the scientific enterprise.

9 Conceptual Studies of Scientific Growth

The discussion to this point has focused on an idealized view of science's epistemic dimension, simply presenting the requirements that have to be fulfilled if one is to be certain of one's conclusions and perhaps suggesting, albeit unintentionally, that these requirements are easily met in the investigation of a particular subject matter. Nothing, of course, could be farther from the case. Demonstrative knowledge represents the summit of scientific knowledge and, as the history of science reveals with its unending account of revisions and theory changes, it is not readily attained. The main problem being addressed in this volume is, in fact, whether it is *ever* attained. To answer that question we obviously have to leave the present and have recourse to the past. There is little point in searching the current literature in science for demonstrations that are taking place at the frontiers of knowledge, for here one would be presumptuous to expect anything more than provisional explanations. And similarly there is little point in canvassing the current literature in the philosophy of science for indications of how certitude can be attained, for example, in the resolution of quantum and space-time paradoxes. Demonstrations are difficult enough to identify when controversies are over and the dust of battle has settled. On the other hand, if no attempt is made to identify them, one is left with the possibility that there is no certitude in science, that *everything* is revisable, and thus with the extreme fallibilist view of science that is increasingly being voiced in the present day.

As already hinted at in the previous chapter, there are two problems that complicate the identification of demonstrations in the history of science. One of these is the extensive foreknowledge that is required before one can even begin to formulate a demonstrative syllogism or propose a causal analysis on which such a syllogism can be based. The other, related to the first, is identifying the suppositions that enter into a demonstrative discourse and gaining assent to them on the basis of observational or experimental evidence. Both of these problems require time for their solution, so much so that it rarely happens that those who propose demonstrations, either explicitly or implicitly, ever live to see them universally accepted within the scientific community to which they are addressed. Yet this situation is anticipated in the way in which Aristotle formulated his canons for demonstration in the *Posterior Analytics*. There he did not envisage solitary scientists checking on their own reasoning (which, of course, they would be well advised to do beforehand), but rather scientists presenting their results to others, who would have to share the foreknowledge required if they were to see it for themselves. Demonstration thus ineluctably has a public aspect. One demonstrates to another, even though to do so one first has to demonstrate to oneself.

In light of these problems with identifying demonstrations, it is additionally difficult to sketch them in such a way that their demonstrative force will be grasped by a universal audience. One way to overcome this obstacle is to go back in time to science's earlier history, when discoveries were simpler and the instrumentation required to duplicate them not as complex as those in the present day. Results then can be more readily understood, even though they are so well known by now that some would regard them as trivial. In this matter, of course, where the very possibility of truth and certitude in science is at question, there is no such thing as triviality. In this context, no finding that is not immediately apparent in sense experience but requires insight and reasoning for its comprehension and assent can be seen as insignificant or unimportant.

In what follows, therefore, a number of conceptual studies are presented in more or less schematic fashion, with the aim being to enable those who have a general familiarity with the subject matter to grasp the point of the demonstration or demonstrations being proposed. An attempt is made to follow the approximate chronological order of the discoveries, so that in this way the simpler demonstrations come first. And the examples proposed are those that were generally recognized by their proponents either as demonstrations in the Aristotelian sense or as results that are true and certain, not open to doubt by those who comprehend the reasons adduced in their support.

9.1 Geometrical Optics: The Rainbow

What causes the atmospheric phenomenon called the rainbow has puzzled men's minds for centuries. The first serious attempt at an explanation was that of Aristotle in the fourth century B.C. Although this was incomplete, it proved to be a remarkably durable explanation. Unfortunately the work in which it was given, the *Meteorology*, was passed on to subsequent centuries without the diagrams that would make it intelligible, so it was not until sometime between A.D. 198 and 211, when Alexander of Aphrodisias reconstructed them, that Aristotle's explanation was understood.[1] From then on, it was often commented on and became the dominant theory until the beginning of the fourteenth century, when its defects were remedied by Theodoric of Freiberg.

Aristotle describes the appearance of both the primary and the secondary rainbow and assigns their cause as a reflection from the sun or other bright object on a reflecting surface. The reflecting surface in this case he identifies as a cloud or discrete series of incipient raindrops which produce an image that appears continuous to the eye. He recognized that one must use demonstrations from the science of optics to explain how this image is produced, and he invoked such demonstrations to sketch the rudimentary geometrical properties of the bow. He was unable to explain correctly, however, how the colors of the rainbow are generated, ascribing the same mechanism to explain both the primary and the secondary bows. Apparently he had no idea of the refraction of light rays and thus saw their reflection as the only way to explain the rainbow's production.

Despite the many attempts to improve on Aristotle's explanation in the intervening centuries, only in the thirteenth century was any substantial progress made. This came about at the University of Oxford, through the work of Robert Grosseteste and Roger Bacon, who, inspired by Aristotle's *Posterior Analytics* and a Neoplatonic "metaphysics of light," performed experiments with the refraction of light rays through crystals and flasks of water. This revived interest in *perspectiva* or geometrical optics, but failed to yield a successful explanation of the rainbow. Grosseteste correctly divined that both the reflection and refraction of rays were involved in the bow's production, but he was far off the mark in explaining how this occurred. Bacon unfortunately negated Grosseteste's advance, for he went back to Aristotle's view that reflection alone is required. Bacon did measure correctly the angle subtended by the primary bow and found it to be 42°. He also followed Aristotle in explaining that the bow's circular shape is caused by reflection from

1. For a detailed account of Aristotle's explanation and its transmission, see Carl B. Boyer, *The Rainbow: From Myth to Mathematics*, New York and London: Thomas Yoseloff, 1959, pp. 37–56. Boyer also treats the work of Alexander of Aphrodisias, pp. 62–65.

groups of raindrops that make the same angle with the eye, because of the equality of the angles of incidence and reflection.[2]

The culmination of the line of research initiated at Oxford is found in Theodoric of Freiberg, a German Dominican who was inspired partly by the teaching of his older confrere Albert the Great that the individual falling drops play an important role in producing the rainbow.[3] Interested in the rainbow and other "radiant impressions" seen in the atmosphere, Theodoric inaugurated a research program that was directed at investigating all the modes of reflection and refraction that are found in the production of these rays. When presenting his results in *De iride et radialibus impressionibus* (On the rainbow and radiant impressions), composed between 1304 and 1311, he cites the *Posterior Analytics* for the methodology behind his *propter quid* demonstrations, which he sees as supplying causal explanations of the phenomena under investigation.[4] Theodoric does not explicitly state that he employed the demonstrative regress in his reasoning, but the way in which he combines invention with resolution in the process is a clear indication that he did. We thus employ the schema for the regress (Sec. 8.6) when setting out his overall results:

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.***

Effect	**Cause**
Radiant phenomena in the heavens, such as rainbows and halos, seem to be produced by	light rays from the sun or other heavenly body being refracted and reflected by spherical drops of water located at determinate positions in the earth's atmosphere.

2. The contributions of Grosseteste and Bacon are also treated by Boyer, pp. 88–102.

3. Boyer details Albert the Great's contribution on pp. 94–99 and Theodoric of Freiberg's on pp. 110–128.

4. Precisely how Theodoric employed Aristotle's *Posterior Analytics* to guide his researches is the burden of my *The Scientific Methodology of Theodoric of Freiberg*, Fribourg: The University Press, 1959. In that and other writings I have used the transcription of *De iride* by Joseph Würschmidt in the *Beiträge zur Geschichte der Philosophie und Theologie des Mittelalters* 12.5–6 (1914), pp. 33–204, occasionally correcting his readings. In what follows I use the new text of M. R. Pagnoni-Sturlese and L. Sturlese in Dietrich von Freiberg, *Opera omnia*, 4:95–268, Hamburg: Felix Meiner Verlag, 1985.

Intermediate stage: ***the work of the intellect, testing to see if this is a cause convertible with the effect, eliminating other possibilities.***
An extensive experimental program, investigating the paths of light rays through spherical droplets, reveals two different modes of refraction and reflection in the interior of the droplets that produce the various colors (red, yellow, green, blue) of rainbows and other radiant impressions when seen from particular positions determined by the angles of entry into, and return from, the droplets. In the case of the primary rainbow, for example, *only* when an observer, with his back to the sun, views falling droplets of rain that form a circular colored arc subtending an angle of 42° from a line that passes from the sun through his eye to a point directly ahead, will he see that bow in the heavens.
Supposition: this and other properties of the rainbow can be proved on the supposition that light travels in straight lines that intersect spheres in points; these calculations then have to be corrected to take account of the fact that the light rays actually have width and breadth and that they intersect spheres in areas that can be determined to the required degree of approximation.

Second progression: ***from the cause, recognized formally as the cause, to its proper effects.***

Cause	**Effect**
light rays from the sun or other heavenly body that pass through spherical droplets of water in the earth's atmosphere and are seen by observers who are properly situated with respect to the sun and the droplets	will appear as one or other type of rainbow, halo, etc., depending on the precise position from which they are viewed by the observers.

Here, as in the previous account of the demonstrative regress, the first stage consists in suspecting that a wide variety of radiant phenomena might be caused by the reflection and refraction of light rays passing through spherical droplets of water in the atmosphere. This is an obscure, or confused, or material grasping of the causality involved, but it is sufficient to prompt Theodoric to begin a research program whose aim would be to identify the proper cause for each of these phenomena. The burden of proof, as heretofore, is then carried by the intermediate stage. Early in his experimentation, while exploring the ways in which light rays are refracted and reflected within prisms of various shapes, Theodoric hit upon the two paths, what he refers to as "modes of radiation" (Lat. *modus radiationis*), that figure importantly in the formation of rainbows. The first of these, shown in Fig. 9.1a, is involved in the pro-

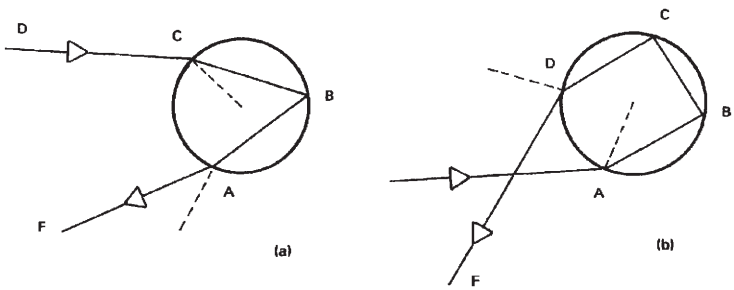

Fig. 9.1 Modes of Radiation in the Rainbow

duction of the primary rainbow and the second, shown in Fig. 9.1b, in the production of the secondary rainbow.

In the case of the primary rainbow, the ray of light that produces colors is incident in the upper part of the drop (C), is there refracted to the back of the drop (B), then is internally reflected to a point (A) below its point of incidence, and finally is refracted there toward the eye of the observer (F). Thus the ray is doubly refracted and singly internally reflected, the refractions taking place at the drop's surface, that is, at the air-water (C) and the water-air (A) interfaces, and the reflection taking place within the drop (B). In the case of the secondary rainbow, the ray of light is incident in the lower part of the drop (A), is refracted into the interior of the drop to a point on the far concave surface (B), is thence reflected to another point (C) higher up on the far concave surface, whence it is reflected to a point on the drop's surface (D) above its point of incidence, and then is finally refracted across the path of the incoming ray toward the eye of the observer (F). Thus the ray is doubly refracted at the drop's surface (at A and D) and doubly reflected in the interior of the drop (at B and C).

In both of these figures, which duplicate those in the manuscripts of Theodoric's *De iride*, light rays are approximated as straight lines. This works for many optical phenomena, but it proves inadequate for dealing with the colors produced by the rainbow. Fig. 9.1, for example, has therefore to be modified to take account of the fact that the rays that produce colors, and the colored rays themselves, have a perceptible width and breadth. Fig. 9.2 duplicates other sketches from the manuscripts that reveal how Theodoric handled this problem. The first, Fig. 9.2a, shows experiments with a hexagonal crystal (a first approximation to the circular cross-section of a raindrop), to show how a ray with a notable width diverges slightly as it is refracted (KP), and then, as it leaves the crystal, diverges even more as it produces colored rays, with the color being indicated by cross-hatching the rays. Colored rays as shown leave the crystal at two places: at the upper right surface (P), as they do when producing the ordinary spectrum, and at the bottom surface (O), as they do in the case Theodoric is investigating. Fig. 9.2b is, of course, basically the same diagram, now applied to a spherical prism, and illustrating the mode of radiation whereby colors are produced by the droplets that form the primary rainbow. Notice that a ray passing through the center of the sphere (GH) produces no colors, whereas one incident in the upper part of the drop (at A) will produce colors similar to those of the ordinary spectrum, going off to the right (EK), and those producing the rainbow, going off to the lower left of the diagram (CM).

The second progression in the schema of the regress is the reasoning Theodoric sees as equivalent to a number of *propter quid* demonstrations, each of which accounts for the properties of a different type of radiant impression in the atmosphere. To give some idea of how these demonstrations are formulated, we here supplement the above regress with the polysyllogism for the primary or lower rainbow. This employs the syllogistic arrangement used above in Sec. 8.1, which is better adapted to identifying the middle terms and the properties to be subsumed under the subject. To understand the various numbered items in the arrangement it will be necessary to consider how the mode of radiation illustrated in Figs. 9.1 and 9.2 is integrated into the diagram Theodoric provides for the primary rainbow. This is reproduced from the manuscripts of *De iride* in Fig. 9.3. Here the sun is at the lower left of the diagram (A), the four bands of drops that produce the colors of the bow on the right (DE, EF, FG, GH), and the paths of the colored rays that

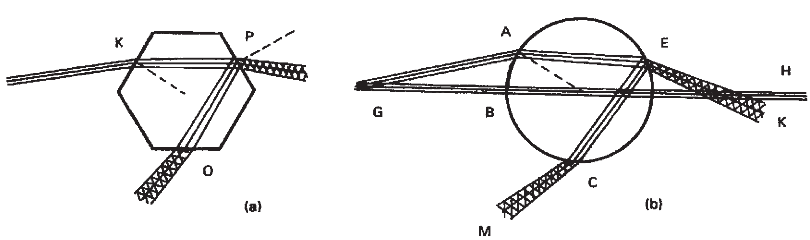

Fig. 9.2 Path Widths in the Production of Colors

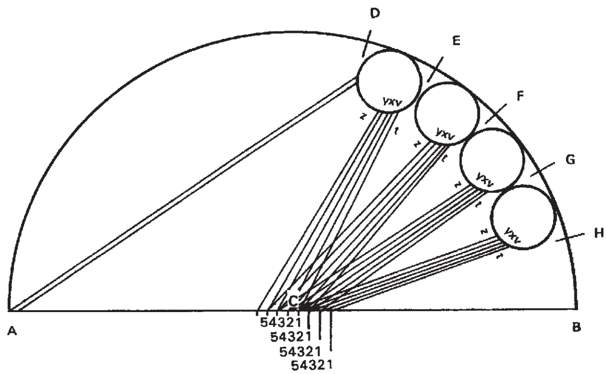

Fig. 9.3 The Production of the Primary Rainbow

are seen by an observer (TVXYZ), converging toward the observer, who is situated in the center of the hemisphere (C). The polysyllogism follows:[5]

S	M	P
[1] The primary or lower rainbow		
	[2] is a radiant phenomenon produced by light rays from a brightly shining heavenly body which are doubly refracted and singly internally reflected through the spherical drops of a dewy cloud or falling rain	
		[3] is generated at a determinate position on the side of the observer opposite from the luminous body, from which angles of incidence and reflection to the luminous body and the observer are equal
	[4] is produced by rays that intersect the surface of each drop at three points determined by nature (AEC in Fig. 9.2b) and mark out an area on each drop (TZ) from which colors are radiated	

5. Adapted from *The Scientific Methodology*, pp. 215–217. I have provided a full English translation of the portions of Theodoric's *De iride* that describe the generation of the primary and secondary rainbows in *A Source Book in Medieval Science*, ed. Edward Grant, Cambridge, Mass.: Harvard University Press, 1974, pp. 435–441.

S	M	P

[5] is extended in an arc that subtends an angle of 22° at the eye of the observer, whose elevation is a maximum when the sun is at the horizon and proportionately less as the sun is above the horizon

[6] is composed of bands of colors that occupy a given area corresponding to bands of drops (DE, EF, etc.) from which different colors are radiated

[7] is reflected from groups of drops at different altitudes situated in a place with a certain latitude (DH) in which the higher and farther drops refract through a greater angle, and made up of partial latitudes (DE, EF, FG, GH) corresponding to the various angles of refraction

[8] is projected in such a way that if red (12) reaches the observer from the highest group of drops (DE), the other colors from those drops (23,34,45) will be projected behind him, while a drop in a lower group (EF) will project red (12) in front of him, yellow (23) to the eye, and green (34) and blue (45) behind him, etc.

[9] is seen by the observer (C) with the highest band red (TV), then yellow (VX), then green (XY), and finally the blue band (YZ) closest to the center of the arc

[10] is different depending on the exact position from which it is seen, and thus "moves" with the observer

[11] is produced by rays that appear in the path of a line rotated about a point on the horizon directly in front of the observer

[12] is always some portion of a circle

[13] which circle is also the base of a cone whose apex is the sun and whose axis passes through the observer

[14] is a semicircular figure when the sun is at the horizon

S	M	P
		[15] is less than a semicircle when the sun is elevated above the horizon, the center of the bow being depressed below the horizon by the same angle as the sun is elevated above it
		[16] is so situated that its center is always in a line with the sun and the eye of the observer
	[17] is produced by droplets contained within a certain critical angle (DCH), below which some rays are reflected to the eye, sufficient to illuminate the drops through which they pass	
		[18] is surrounded by a band verging towards whiteness below the concave portion of the bow and the horizon and
	[19] above which there is no appreciable reflection to the eye	
		[20] is surrounded by an obscure area verging on darkness above the convex portion of the bow.

In this schematic arrangement, as indicated the subject [1] is the primary rainbow, while the various middle terms ([2], [4], [7], [11], etc.) are in the order of either material or efficient causality, and the passions or properties ([3], [5], [6], [8], etc.) are all qualitative or quantitative modalities of the bow and its surrounding area, which in turn are reducible to either or both of these causes. Most of the properties are understandable on their own terms; those listed in [18] and [20], however, may pose a problem. They refer to a phenomenon first discovered by Alexander of Aphrodisias and thus known as an "Aphrodisian band"—a phenomenon Alexander was unable to explain. It appears that Theodoric was the first to account for it in terms of the mode of radiation producing the bow. With the exception of the angle in [5], which appears to be an error in transcription and should be doubled, it is noteworthy that all of these are valid demonstrations of observable properties of the lower bow.[6] In addition to the properties listed here, Theodoric

6. The arc for the halo subtends an angle of 22°, and Theodoric might have confused this with the angle for the primary rainbow. Also, some commentators have mentioned that his "altitude circle" (the large semicircle in Fig. 9.3) requires correc-

also addresses the question whether the rainbow is real or not. Roger Bacon had maintained that it was not, that it was merely an appearance. Theodoric disagreed on that point. He insisted that the colors are real, but their being is that appropriate to an optical image, the way one's likeness appears in a mirror.

The polysyllogism for the secondary or upper rainbow is very similar to that for the primary or lower rainbow. The main difference is found in the mode of radiation whereby the secondary rainbow is produced. As a consequence of the longer path and the additional reflection, the ray of the secondary rainbow is weakened, with the result that this bow is always fainter than the first. Also, because of the greater area or expanse of the bow, more raindrops are required and the secondary is seen less frequently than the primary. The second reflection also reverses the order of colors, so that in the secondary bow the outermost color is blue and the innermost color red, opposite to what it is in the primary; moreover, it is surrounded by an "Aphrodisian band" verging toward whiteness and not darkness, again opposite to the primary. Finally, the mode of radiation requires that the secondary bow appear higher in the heavens than the primary, so that it subtends an angle at the eye of the observer that is 11° larger than that of the lower bow.

All of the aforementioned properties of primary and secondary rainbows are demonstrated correctly by Theodoric in his lengthy treatise, wherein he adduces extensive observational and experimental evidence in their support. He identifies the causes that explain these properties first in general and then in detail for each of the bows. The formal cause or form is the radiant impression we call a rainbow: it extends above the horizon in the atmospheric region and is in the shape of an arc, with the arch on top and with both extremities touching the horizon when it is fully formed. The material cause or matter is the subject body in which this impression comes to be. It is twofold: either a dewy cloud, that is, a cloud resolved into spherical droplets suspended in and around the place of generation of the bow, or a collection of drops released from a cloud and falling as rain. Although in the latter case the drops are continually moving downwards, the fact that some drops succeed others in the same place causes the radiant manifestation to appear in that place. The efficient cause is radiation from a brightly shining heavenly body such as the sun, and this is found in the alternate modes already described for the primary and secondary bows. Theodoric does not discuss the bow's final

tion. The problem here is how this circle is to be interpreted; see the discussion in Loris Sturlese's introduction to the *De iride* in the latest edition, pp. xxxix-xli.

cause, but he evidently conceives this as the form that terminates the process by which the bow is generated and so he identifies it with the formal cause.

Obviously, in demonstrations of this type, material and efficient causality carry the burden of proof. This is true of all radiant phenomena in the earth's atmosphere, as Theodoric makes clear at the outset of his treatise, for these are all properties of water globules suspended or falling in air when properly illuminated and seen under the specified conditions. In this way of viewing the rainbow, it is itself a property of clouds or falling droplets, and these are its material cause, the ontological subject of the above demonstrations. The middle terms are then reducible to various modalities of the efficient cause, namely, light rays passing through the droplets in the different modes of radiation that produce the observed phenomena. The agent from which the rays come is a brightly shining heavenly body or other luminous source. How the source produces such rays or how fast light rays travel is not at question here. They are the causes of radiant phenomena; what is *their* cause is left open for further investigation.

The supposition that underlies these demonstrations is one common to all demonstrations in geometrical optics, namely, that light rays travel in straight lines. Because of the fact that the rainbow appears with bands (and not simply lines) of color, however, Theodoric found it necessary to oversimplify the mechanism by which they are produced and first treat rays as lines (Fig. 9.1), and then modify the explanation to see them as columns, that is, as lines with a width and breadth, so that they can project the colors as spread out over areas (Figs. 9.2–3). In this respect his demonstrations were perfectible and later improved upon by René Descartes and Sir Isaac Newton, as will be seen later in this chapter. It is important to note that these improvements do not negate the demonstrative force of Theodoric's arguments, any more than the discovery that the earth's shape approximates an oblate spheroid nullifies the demonstration offered above (Sec. 8.1) that the earth is a sphere. This point is discussed more fully in the next chapter (Sec. 10.1).

9.2 Planetary Astronomy: The Moon and the Planets

Apart from the shape of the moon and its various aspects or phases, as already discussed (Sec. 8.5), little was known about earth's closest heavenly companion until Galileo made his exciting discoveries with the telescope in 1609–1610. Others before him had constructed telescopes, and some had even looked at the heavens with them, but none could formulate the "necessary demonstrations" Galileo would propose on the basis of his observations, and to which he referred repeatedly in his *Letter to the Grand Duchess Christina*.[7] Not only would these expand our knowledge of the moon, but they would call attention to two new phenomena in the heavens, the satellites of Jupiter and the phases of Venus, all of which would provide new evidence in support of the Copernican system.

The Moon. Between November 30 and December 18 of 1609, Galileo studied the moon with his new instrument and made no fewer than eight drawings of the appearances he observed. On January 7, 1610, he wrote to Antonio de' Medici in Florence that, from the data he obtained, "sane reasoning cannot conclude otherwise" than that the moon's surface contains mountains and valleys similar to, but larger than, those spread over the surface of the earth (GG10: 273). Thus, within a month, by his own account, Galileo had demonstrated to his personal satisfaction that there are mountains on the moon.

How he did so offers a striking illustration of how he could adapt the demonstrative regress explained in his *Tractatio de demonstratione*, which he had earlier employed in explaining the moon's aspects and phases in his *Trattato della sfera* (Sec. 8.6), to formulate new scientific claims. The regress that supports the "sane reasoning" to which he referred in his letter to Antonio de' Medici may be schematized as follows:[8]

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.***

Effect	**Cause**
sharply defined spots on illuminated parts of the moon's surface, an irregular line at the terminator, with points of light emerging in the dark parts	suggest that the surface of the moon is rough and uneven, with bulges and depressions (GG3.1:62–63)

7. Galileo makes reference to these "necessary demonstrations" some forty times in the *Letter*. All of the references are examined by Jean D. Moss in her "The Rhetoric of Proof in Galileo's Writings on the Copernican System," *Reinterpreting Galileo*, ed. W. A. Wallace, Washington, D.C.: The Catholic University of America Press, 1986, pp. 179–204. See also her "Galileo's *Letter to Christina*: Some Rhetorical Considerations," *Renaissance Quarterly* 36 (1983), pp. 547–576.

8. Adapted from *Galileo's Logic of Discovery and Proof*, pp.198–201.

Intermediate stage: ***work of the intellect, testing to see if this is a cause convertible with the effect, eliminating other possibilities.***
The dark part of the spots have their side toward the sun; shadows diminish as the sun climbs higher: points of light in the dark area gradually increase in brightness and size, finally connect with the dark area; "we are driven to conclude by necessity" that *only* prominences and depressions can explain the appearances "for certain and beyond doubt" (GG3.1:64–69)

Second progression: ***from the cause, recognized formally as the cause, to its proper effects.***

Cause	**Effect**
changing illumination from the sun's rays on mountains of calculable height rising from the moon's surface	produce all of the observed appearances (GG3.1:69–70)

Like the demonstration of the moon's phases in Sec. 8.6, this is not a topical argument but one that purports to yield certain knowledge based on true causes. The causes again are formal accidental causes (figure or shape), although they too presuppose the exercise of efficient causality (the passage of light rays). The figure or shape is that of a natural body capable of reflecting light, and the laws whereby it does so are those of geometrical optics. The irregular shape of the terminator (the boundary separating the light parts from the dark parts of the moon's surface) is not a mathematical line but one traced out by light rays impinging on the surface. Thus the demonstration, like Theodoric's, is that of a mixed science, mathematical physics, not that of pure mathematics or of natural philosophy as such.

Suppositions are likewise involved in the demonstration. Many of these are those required for geometrical optics in general, such as that light rays may be treated as straight lines. Moreover, in the first progression the causes materially suspected, bulges and depressions on the moon's surface, might be seen only conjecturally and so entertained simply as a supposition. By the conclusion of the intermediate stage, however, the conviction would be generated that this supposition is true and so can serve as a premise in a demonstration of the reasoned fact. Thus the regress itself registers a growth of knowledge throughout its stages, as one proceeds from an obscure or confused grasping of the cause to its distinct elaboration in terms of quantifiable predicates. Some of those who first examined Galileo's argument here, including Christopher Clavius, did not experience this knowledge growth and so did not give immediate assent. This frequently happens, of course, with "necessary demonstrations," for reasons to be examined in the following chapter.

Jupiter: On the very evening Galileo wrote to Antonio de' Medici that he had conclusively demonstrated the existence of mountains on the moon, he noted a strange phenomenon, namely, that the planet Jupiter was "accompanied by three fixed stars" (GG10:277). That was on January 7, 1610. The next night Galileo turned his telescope on the heavens again, hoping to see that Jupiter had moved to the west of these stars, as Ptolemaic computations then predicted (GG3.1:80). To his surprise this time he found the planet to be east of them. His attempt to resolve that anomaly led him to a program of observing Jupiter and its strange companions whenever he could over a two-month period. By January 11th he had concluded that they were not fixed stars that could be used to determine the motion of Jupiter, but rather that they were small bodies, never observed before, that were moving along with Jupiter and actually circling it. "I therefore arrived at the conclusion, entirely beyond doubt *(omnique procul dubio)*," he wrote, "that in the heavens there are three stars wandering about Jupiter like Venus and Mercury around the sun" (GG3.1:81). On January 13th he saw a fourth object for the first time, and by the 15th he had convinced himself that it was doing the same (GG3.1:82). So within a week of his curiosity having been aroused he had completed the demonstrative regress and had convinced himself that Jupiter has four satellites revolving about it, as it made its own majestic revolution around the center of the universe (GG3.1:80–95).

The reasoning process Galileo employed over the course of that week and subsequently may be schematized as follows:[9]

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized as the cause.***

Effect	Cause
four little stars accompany Jupiter, always in a straight line with it, and move along the line with respect to each other and to Jupiter	possibly indicating that the stars are satellites of Jupiter, circling around it at various periods and distances from it

Intermediate stage: ***the work of the intellect, testing to see if this is a cause convertible with the effect, eliminating other possibilities.***

Sixty-five observations between January 7 and March 2, analyzing in detail their variations in position, how they separate off from Jupiter and each other and merge with them in successive observations; inference to the *only* possible motion that explains these details; concluding "no one can doubt" *(nemini dubium esse potest)* that they complete revolutions around Jupiter in the

9. Adapted from *Galileo's Logic of Discovery and Proof*, pp. 201–203.

plane of the ecliptic, each at a fixed radius and with its characteristic time of revolution (GG3.1:94).

Second progression: ***from the cause, recognized formally as the cause, to its proper effects.***

Cause	**Effect**
four satellites of Jupiter always accompany it, in direct and retrograde motion, with their own distances from it and periods of revolution (GG4:210), as it revolves around the center in twelve years	seen on edge produce the appearance of four points of light, moving back and forth on a line with the planet and parallel to the ecliptic

Much the same observations may be made about this demonstration as about the previous illustrations of the demonstrative regress. Like them, it purports to be apodictic and not merely dialectical. It is concerned with the mathematical properties of natural or physical bodies and so pertains to the middle science of mathematical astronomy. The basic supposition is again that light travels in straight lines. Over and above that, one has to know enough projective geometry to recognize that satellites circling around a planet in its equatorial plane will, when seen on edge, appear to be moving back and forth along a line parallel to the planet's equator and along the elliptic. Galileo quickly saw the convertibility of the geometry involved, went from the straight-line motion he actually observed to the circular motion that alone could cause it, and then regressed from the cause back to the effects he had so carefully observed. Finally, the argument supposes that the observational evidence presented by Galileo is correct and that it can be verified, as he claims, by anyone possessing a good twenty-power telescope. This supposition definitely slowed the acceptance of the demonstration in Galileo's day, about which more will be said in the following chapter.

Venus. While Galileo was making his observations of Jupiter, Venus was in the morning sky and not in a favorable position for viewing. Although he suspected that it was going around the sun, as indicated in a passage cited above, he had no way of confirming that suspicion. It was not until October of 1610 that Venus appeared in the evening sky and Galileo could seek the confirmation he sought. Just as he was about to announce he had obtained it, he received a letter from his former student Benedetto Castelli, inquiring whether Venus as seen through the telescope was "sometimes horned and sometimes not" (GG10:481). In Brescia at the time and lacking a telescope himself, Castelli apparently had the same thought as Galileo and saw this appearance as necessary proof of Venus's revolution around the sun. Galileo quickly wrote back to Castelli with an affirmative answer, explaining that he had been observing Venus with his instrument for about three months and describing what he had seen. Sometimes Venus was horned and sometimes it was not, namely, when it showed a full or half disk. It therefore emulates the figures of the earth's moon, as Galileo put it when deciphering an anagram he had earlier sent to Kepler (GG3.1:183–199), and so offers conclusive proof that it revolves around the sun.

The argument that would convince one of the truth of this conclusion is very similar to the explanation of the phases of the moon given above, although the geometry is different in the two cases. In a heliocentric system, planets that come between the earth and the sun, Mercury and Venus (inferior planets), appear differently from those that are farther out and so do not, such as Jupiter and Saturn (superior planets). As seen from a moving earth, inferior planets at some time during their synodic periods show crescent phases; superior planets, on the other hand, never have crescent phases, though they have gibbous phases when in quadrature with the earth and otherwise are seen as full. The basic reason is that inferior planets, like the moon, come between the earth and the sun and so can receive the partial illumination that shows up in the crescent phase. Always being within the earth's orbit, inferior planets cannot be in opposition to earth; instead they have two conjunctions with it, an inferior conjunction when closest and a superior conjunction when farthest away. During the first they are "new" and during the second "full"; in between they are in quadrature and exhibit the "half-moon" appearance. Thus they go through the same phases as the moon. The major difference is that at inferior conjunction the planet is very much larger than it is at superior conjunction, whereas the moon, maintaining the same distance from the earth, appears to be of the same size throughout the phases.

In light of these considerations, the demonstrative regress for proving that Venus is orbiting the sun may be summarized as follows:[10]

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.***

Effect	**Cause**
Venus manifests the same phases as the moon but changes in size as it goes through the phases, being smallest when it is full	could result from the fact that Venus is in orbit around the sun and is seen at varying distances from the earth

10. Adapted from *Galileo's Logic of Discovery and Proof*, pp. 203–207.

Intermediate stage: ***the work of the intellect to see if this really is the cause, eliminating other possibilities.***

The progression of shapes of Venus as it is observed through a good telescope, from full to semicircular to new and back to full again, with corresponding changes in sizes from small to large and back again, has *only* one possible explanation: Venus is located between the earth and the sun (that is, it is an inferior planet) and it is in orbit around the sun.

Second progression: ***from the cause, recognized formally as the cause, to its proper effects.***

Cause	**Effect**
Venus's motion around the sun as an inferior planet	explains changes in size and shape throughout its orbit

Once again, what is proposed is a demonstration, not a dialectical argument, based on suppositions drawn from projective geometry and geometrical optics as well as on the observational evidence presented by Galileo. With regard to the intermediate stage, the necessity of the conclusion does not follow directly from the observations and can be seen only with the eye of the mind. Both Galileo and Castelli seem to have been aware of this and the complication it introduced to the presentation of their case. In his letter Castelli had remarked that, if the appearances were as he thought they would be, they would "be a sure means of convincing any obstinate mind." In his reply Galileo reacted to this by noting that demonstrations can convince those "who are capable of reason and desirous of knowing the truth," but unfortunately that their adversaries were not of this type (GG10:503–504). Thus he was under no illusion about the ability, and the willingness, of his audience to complete the intermediate stage successfully, experience the growth of knowledge it entails, and so agree with the conclusion he had demonstrated.

With regard to the second progression, it should be noted that this concludes only that Venus goes around the sun and permits no inference that the earth does also. Thus it disproves the Ptolemaic system without clearly confirming the Copernican alternative, since it still leaves open the Tychonian system as a possibility. However that might be, up to this point Galileo had not openly embraced Copernicanism. Now, with the evidence of the moon's earth-like appearance at hand, the knowledge of Jupiter's moons, and finally of Venus's phases, he seem to have been convinced of the superiority of the Copernican system and began to say so publicly.

9.3 Statics and Kinematics: Falling Bodies

Long before his discoveries with the telescope, Galileo was interested in the problem of falling motion and had proposed new demonstrations that would overthrow Aristotle's teachings on this subject. This is evident from his early treatises on motion, composed in 1590, shortly after the *Tractatio de demonstratione* and now preserved as his *De motu antiquiora*. The main project here was one of employing the statics of Archimedes to revise the Aristotelian account. The effort was not successful largely because of the suppositions Galileo employed, but it is instructive because it marked an important step in his search for the principles on which a new science of motion would be erected. It also shows Galileo making use of the demonstrative regress to correct Aristotle's view of what causes the swiftness and slowness of natural motions. At the outset of his investigations, Galileo admits that, though "what we seek are causes of effects, these causes are not given us in experience" (GG1:263). In other words, natural causes are in large part hidden causes, and they can be discerned only from a careful study of the effects they produce—precisely the situation that would require one to employ the *regressus demonstrativus*.

Experiments at Pisa. Galileo's investigation is quite lengthy, and here we shall examine only the reasoning by which he arrives at one conclusion, that relating to the effect of the medium on speed of fall. This states that, in the same medium, bodies of the same material but of unequal volume move naturally with the same speed. The technique Galileo uses is that of indirect proof, favored by mathematicians such as Archimedes: it consists in setting up a dichotomy between Aristotle's teachings and his own, reducing the former to an impossibility or an absurdity (Sec. 8.4), and then urging the truth of his own position. The dichotomy he employs here is that *either* bodies of the same material and of different volumes fall with the same speed in the same medium, *or* they fall at different speeds following the rules given by Aristotle in *De caelo* III.2 and IV.4. Galileo's solution invokes Archimedes' buoyancy principle to remove the second alternative and so endorse the first. His argument may be schematized as follows:[11]

11. Adapted from *Galileo's Logic of Discovery and Proof*, pp. 250–251.

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.***

Effect	**Cause**
Bodies of the same material and of unequal size fall at the same speed in the same medium through which it falls	since speed of fall is determined by the weight of the body in the medium

Intermediate stage: ***the work of the intellect to see if this really is the cause, eliminating other possibilities.***

Supposition: heavy bodies move downward by reason of their weight *(gravitas)*, and thus their speed of fall is directly proportional to their weights (GG1:262).

To hold, as Aristotle does, that speed of fall is directly proportional to absolute weight contradicts experience, since if two stones are dropped from a high tower, one twice the size of the other, the larger does not reach the ground when the smaller is only halfway down (GG1:263).

The essential cause *(causa per se)* of the body's speed is thus not its absolute weight but its specific weight, that is, its weight less the weight of a volume of the medium equal to its own volume. Such specific weight is the same for all bodies of the same material and of unequal size falling in the same medium (GG1:264).

Accidental causes *(causae per accidens)* such as the shape of a body may cause variations in speed, but these are slight and may be neglected (GG1:266).

Second progression: ***from the cause, recognized formally as the cause, to its proper effects.***

Cause	**Effect**
Bodies of the same material and of unequal size have a constant specific weight in a given medium	neglecting accidental causes, fall at the same speed in a given medium (GG1:266)

Note here the genus of causality on which the proferred demonstration is based. Galileo is still working under the Aristotelian supposition that downward motion is caused by a motive power in the heavy object, its *gravitas*, and thus his argument invokes an efficient cause. This also implies that speed of fall in the same medium is uniform, since the motive force and the resistive force then remain constant throughout the motion. Galileo's departure from Aristotle is not in the cause itself, but rather in his adoption of the Archimedean principle denying that speed of fall is regulated by the absolute weight of the body, its *gravitas*; rather it is regulated by the body's relative weight, its *propria gravitas*, that is, its weight in the medium through which it moves. Already enunciated by Giovanni Battista Benedetti, this becomes what Galileo here identifies as the "true cause" of the speed of fall of bodies in various media (GG1:272–273).

Later in the *De motu antiquiora* Galileo breaks new ground by studying the ratios of motions of balls rolling down an inclined plane. Although static treatments of weights on inclined planes were common in mechanical treatises of the time, including those of Jordanus Nemorarius, Niccolò Tartaglia, and Guidobaldo del Monte, Galileo was the first to attempt to derive ratios of motions along such planes, as he claimed, "from principles of nature that are known and manifest" (GG1:296). Apparently he thought that, if the effective weight of a body can be decreased by positioning it on an incline (as it can be decreased by placing it in a more buoyant medium), its velocity down the incline will be similarly slowed and thus made more amenable to investigation. The conclusion he suspected was that the body's weight on the incline, compared to that in free fall, would be decreased by the same ratio as the vertical height of the incline to the length along the incline. The reasoning process whereby he arrived at this result need not be traced here; suffice it to note that it employs a demonstrative regress similar to that already sketched. It also invokes the same supposition, plus additional suppositions about the roundness of the ball and the smoothness of the incline, so as to eliminate as many accidental causes *(causae per accidens)* as possible.[12]

Galileo uses the term *periculum* for test or experiment five times in this treatise. One occurrence is in connection with the first supposition noted above, the Aristotelian principle that speed of fall (V) is directly proportional to the falling body's weight (W). Galileo writes that if one performs the *periculum* or experiment, the ratios he has calculated will not actually be observed, because of "accidental causes" he has been unable to eliminate (GG1:273). In another place, where he had advanced the supposition that any given body can be moved on a plane parallel to the horizon by a force smaller than any given force, he goes on to add that one should not be surprised if a *periculum* or experiment does not verify this, for two reasons: external impediments prevent it, and a plane surface cannot be parallel to the horizon because the earth's surface is spherical (GG1:301). But if these difficulties can be overcome, his proofs will have the same validity as those offered by "the superhuman

12. For details of the argumentation, see *Galileo's Logic of Discovery and Proof*, pp. 251–255.

Archimedes, whose name [he] never mention[s] without a feeling of awe" (GG1:300).

This extensive study of motion, and the above is but a small excerpt from it, took place around 1590, while Galileo was teaching at the University of Pisa. He obviously had the intention of publishing it, but because of his failure to confirm experimentally the suppositions on which it was based, and the doubts this induced about his having discovered the "true causes" he alleged, he withheld it. He kept the manuscript in his possession, nonetheless, and when he finally did discover the correct law of falling bodies he inserted a draft of his discovery among the folios of the manuscript containing his *De motu antiquiora*, thus signaling its role in the discovery process.

Experiments at Padua. The discovery did not take place for over a decade, until Galileo was well established at the University of Padua, and only shortly before his famous findings with the telescope in 1609. In the series of experiments in which he did so, now known as the "table-top" experiments, Galileo used the inclined plane again to establish (1) that the speed of fall is not uniform, as he had supposed in 1590, but is continually accelerated, (2) the correct speed law, that the speed is proportional not to the distance of fall, as he had thought in 1604, but to the square root of the distance, (3) the correct distance law, that the distance of fall is itself proportional to the square of the time of fall, and (4) that the path a body follows when projected horizontally at uniform speed and then allowed to fall under the influence of gravity is a semi-parabola. The inclined plane was used in these experiments, but in a very special way, as we are about to explain. And all of these results can be schematized in quasi-syllogistic form using the demonstrative regress, just as with the 1590 experiments already discussed.

Around 1602, while in correspondence with Guidobaldo del Monte, Galileo experimented with the pendulum as an alternative to the inclined plane, because, although the bob of the pendulum moves along the arc of a circle rather than a chord, it eliminates the surface friction always present on the plane. By this time Galileo had already rejected the Aristotelian dynamic law, that speed of fall is uniform and simply proportional to weight. In 1604, as already mentioned, he wrote to Paolo Sarpi stating that speed increases with distance of fall, and from this principle he was trying to deduce various properties of falling motion (GG10:115–116). Shortly after that he apparently initiated experiments with an inclined plane situated on the top of a table with its base at or near the table's edge that allowed the ball to roll down the incline and

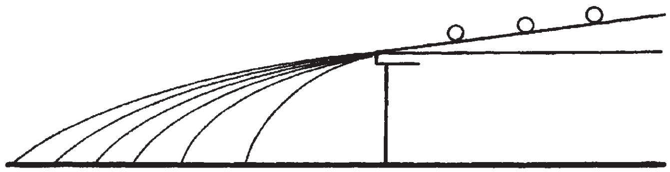

Fig. 9.4 Projection from a Fixed Incline

then drop freely to the floor. The plane was here being used differently than in the 1590 experiments; now its function was merely to control the speed and direction of the ball at the point of leaving the table, not to be an instrument on which measurements of speed and time of roll can be directly made. These experiments were totally unknown until about 1972, when Stillman Drake uncovered the folios that give evidence of them.[13] Since then they have been analyzed in detail and duplicated by Drake, Ronald Naylor, David Hill, and others.[14] Collectively their results show that Galileo was engaged in a serious research program in the first decade of the seventeenth century, achieving an experimental accuracy within three percent when testing most of his calculated results.

As shown in the next three figures, this program made use of three different, but connected, types of experiment, probably made in the progression shown in the figures as here ordered. The first type, Fig. 9.4, was designed to ascertain the correct speed law. A ball was rolled down a fixed incline with various distances of roll and thus projected to the floor at different distances from the foot of the table. On Galileo's sketch the lengths of projection along the floor are listed as 253, 337, 395, 451, 495, 534, and 573. Hill, in attempting to duplicate Galileo's figures, has found that increasingly longer lengths of roll down an inclined plane inclined at an angle of 12° to the table top, with these lengths standing in the ratio of 1:2:3:4:5:6:7, will yield Galileo's figures approximately.

13. "Galileo's Experimental Confirmation of Horizontal Inertia," *Isis* 64 (1973), pp. 291–305; also *Galileo at Work: His Scientific Biography*, Chicago: The University of Chicago Press, 1978.

14. The key articles are Ronald Naylor, "The Search for the Parabolic Trajectory," *Annals of Science* 33 (1976), pp. 153–172; "Galileo's Theory of Projectile Motion," *Isis* 71 (1980), pp. 550–570; and "Galileo's Method of Analysis and Synthesis," *Isis* 81 (1990), pp. 695–707; and David K. Hill, "A Note on a Galilean Worksheet," *Isis* 70 (1979), pp. 269–271; "Galileo's Work on 116v: A New Analysis," *Isis* 77 (1986), pp. 283–291; and "Dissecting Trajectories: Galileo's Early Experiments on Projectile Motion and the Law of Fall," *Isis* 79 (1988), pp. 646–668.

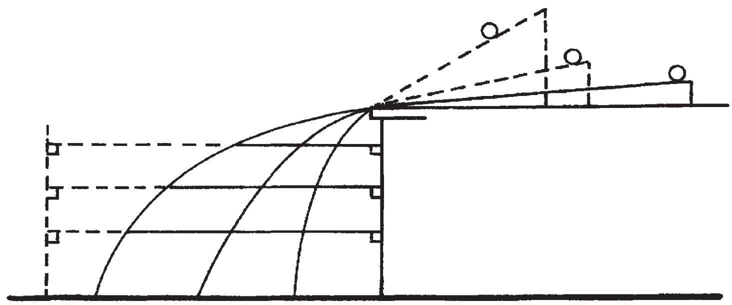

Fig. 9.5 Projection from Variable Inclines

Hill's analysis of these data would seem to confirm that the distance of horizontal projection, which is a measure of the ball's speed on leaving the incline, is as the square root of the length of roll down the incline.[15] An argument based on the similarity of the circumstances would seem to indicate that velocity of fall is not proportional to distance of fall, as Galileo had conjectured in his letter to Sarpi, but rather is proportional to the square root of that distance.

With this knowledge in hand, Galileo then began to work on defining the characteristics of the curves that result when the angle of incline is varied. This is the second type of experiment, shown in Fig. 9.5. This figure, as reconstructed by Hill in his "Dissecting Trajectories" article (pp. 647–648), is based on a manuscript drawing on which Galileo had written numerals for all the horizontal intervals at the different vertical levels. According to Hill's calculations, the three curves approach a parabolic form the farther they extend away from the table. He speculates that they were generated by rolling balls down inclines of various angles of inclination, with the balls then being allowed to drop through different vertical intervals, either to the floor or to a board set at some intermediate height between the floor and the table top. Hill identifies four different heights and three different angles of inclination used in the ex-

15. For Hill's analysis, see his "Dissecting Trajectories," pp. 658–659. If one takes the starting length of roll at 400, the successive lengths will be 800, 1200, 1600, 2000, 2400, and 2800. Taking the square root of the middle figure in this sequence, 1600, and fitting it to the middle figure in the horizontal projections, one obtains a sequence very similar to Galileo's, namely, 226, 319, 390, 451, 505, 552, and 596. These figures suggest that the speed of roll is proportional not to the distance of roll but to the square root of that distance.

periment. Since the curves approach a semi-parabola as the angle of incline decreases, this would seem to suggest that straight horizontal projection after a roll, which cannot be achieved with this experimental setup, would yield the sought-after parabolic form.

Galileo's problem then became one of achieving such a projection while at the same time having a way to vary and measure the ball's velocity on leaving the table top. His solution, as Hill conceives it, is shown in the two configurations of Fig. 9.6. That on the left (Fig. 9.6a), based on sketches in a Galileo manuscript, illustrates his attempt to design deflectors that would impart different trajectories to a ball leaving the table after a steep vertical drop. That on the right (Fig. 9.6b) shows an experiment Galileo performed with the deflector that came closest to yielding a horizontal projection after rolls of measured height down an inclined plane. This is the famous diagram of folio 116v of MS Gal. 72, which has been subjected to many analyses since Drake first called attention to it in 1973. This figure turns out to be crucial for the new science of motion, for it contains the key to the definition of naturally accelerated motion that later serves as its first principle.

In numerals he wrote on the right-hand diagram (Fig. 9.6b) Galileo lists the height of the table, 828 units, and also various heights of fall down the incline, namely, 300, 600, 800, 828, and 1000 units. Along the horizontal at the level of the floor he then records measurements of horizontal projection, writing the figures 800, 1172, 1328, 1340, and 1500. For the last four figures he then provides a second set of numerals, namely, 1131, 1306, 1330, and 1460. These presumably are Galileo's calculations of what the distances should be if the 800 figure is taken as the baseline and one is attempting to show that successive heights of fall

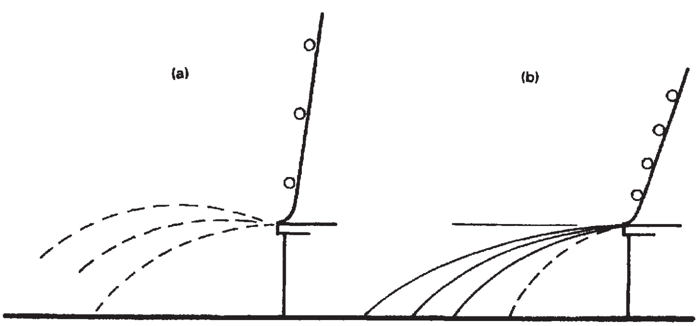

Fig. 9.6 Experimenting with Horizontal Projections

are in the same ratio as the square of the distances of horizontal projection. Should this relationship be verified experimentally, one would have proof that the velocity of fall is directly proportional to the time of fall.[16] Thus the key result that emerges from these experiments is that the speed of bodies in free fall, instantiated by balls that are no longer on the incline but have left it and are falling naturally, varies directly as their time of fall. From this principle, explicitly stated at the beginning of the Third Day of the discourses of the *Two New Sciences*, Galileo derives most of the propositions he presents in the Third and Fourth Days of that work. His reasoning in establishing that principle may be abbreviated as follows:[17]

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.***

Effect	**Cause**
The various properties of heavy bodies moving with a motion that is naturally accelerated	are probably caused by their falling at a speed directly proportional to their time of fall

Intermediate stage: ***the work of the intellect, testing to see if this is a cause convertible with the effect, eliminating other possibilities.***

This is proved kinematically, because only a falling speed directly proportional to the time of fall can produce distances that satisfy the odd-number rule and the times-squared rule in vertical fall, the double-distance rule when the vertical speed is converted to horizontal speed, and the semi-parabolic

16. The proof is sketched in my *Prelude to Galileo*, pp. 154–156, and may be summarized as follows: By 1604 Galileo already knew from his studies of motion down an inclined plane that the distances of travel down the incline vary as the squares of the times, i.e., $s_1/s_2 = (t_1/t_2)^2$ [1]. The additional experiments on fol. 116v were designed to show that a ball, after descending down an incline set on a table top and being projected horizontally along a line parallel to the table's surface, will travel various distances (D) depending on the height through which it descends (H) before reaching the floor. He used the experimental setup to show that $(D_2/D_1)^2 = H_2/H_1$ [2], within an accuracy of about three percent. Since the distance of travel of the ball along the incline is proportional to H, it is true that $s_1/s_2 = (t_1/t_2)^2 = H_1/H_2$ [3]. Also, when the ball leaves the table top, since the velocity it acquires during any fall (v_H) is directed horizontally, the horizontal distance of travel by the time it reaches the floor (t_h), where h is the height of the table, will be $D_H = v_H t_h$ [4]. Since t_h is constant for all experiments, this is equivalent to saying that $D_1/D_2 = v_1/v_2$ [5]. Squaring both sides of [5], and making use of the experimentally verified relationships [2] and [3], one may then write $(v_1/v_2)^2 = (D_1/D_2)^2 = H_1/H_2 = (t_1/t_2)^2$ [6], or, taking the square root of the resulting extremes, $v_1/v_2 = t_1/t_2$ [Q.E.D.]

17. Adapted from *Galileo's Logic of Discovery and Proof*, pp. 270–273.

path when free fall occurs after the vertical speed has been converted to horizontal speed—by geometrical demonstration, from the supposition *(ex suppositione)* that all impediments such as friction, the resistance of the medium, and all other accidental factors have been removed.

It is also argued from physical considerations: for nature itself *(instituti ipsiusmet naturae)* causes the falling motion of a heavy body, which is a natural motion, to increase in the simplest way: by adding equal increments to the speed in equal intervals of time.

It is also argued from disproof of the simplest alternative, since speed does not increase directly with the distance of fall but rather with the square root of that distance.

It is confirmed experimentally, for physical experiments *(naturalia experimenta)* show that all these metrical properties are verified within degrees of accuracy that allow for slight departures owing to impediments and accidental causes (GG2:261, 8:197).

Second progression: ***from the cause, recognized formally as the cause, to its proper effect.***

Cause	**Effect**
A heavy body that is naturally accelerated in free fall at a speed that is directly proportional to its time of fall from rest	manifests metrical properties described by the odd-number, times-squared, and double-distance rules and by paths of semi-parabolic projection

As can be seen here, the demonstrative regress is employed once again to arrive at the true cause, what becomes for Galileo the definition of naturally accelerated motion. The first progression is *a posteriori,* from effect to cause, and the second *a priori,* from cause to effect. Undoubtedly the new approach was stimulated by the series of experiments just described, which led to Galileo's realization that a revised "speed law" was now required. As heretofore, the intermediate stage, the work of the intellect, carries the burden of proof. Actually its wording as shown here follows closely Galileo's Latin text in his draft of this passage, the *De motu accelerato* fragment now bound in the manuscript containing the *De motu antiquiora* (GG2:226), where Galileo inserted it after writing it out. It also appears later in the *Two New Sciences*, and with almost identical wording (GG8:198).

Note that the demonstration here, like the earlier ones, is explicitly made *ex suppositione,* that is, on the supposition that all impediments to the falling motion, such as friction, resistance of the medium, and accidental factors, have been removed. The proof is based partly on the elimination of the simplest alternative, that speed of fall is based on distance of fall, as Galileo himself had first thought. But the direct proof is experimental. Note the reference to "physical experiments," pointedly in the plural. The reference is not to the simple inclined-plane experiment described in the *Two New Sciences,* as it has commonly been taken, but to the whole gamut of experiments, "table-top" included, performed at Padua before the discoveries with the telescope. Note further that Galileo no longer identifies the weight of the falling body as the cause of its fall, as in his early formulations. Now he is interested solely in the kinematic factors that bear on the quantitative aspects of naturally accelerated motion. As for the ultimate physical cause of the fall, he identifies this simply as "nature," the ultimate explanatory principle in Aristotelian physics. So he himself is working unambiguously in the tradition of a mathematical physics, a "mixed" or "middle science." What he proposes to do for dynamics is what Archimedes did for statics, that is, provide a hitherto unknown science of local motion based on mathematics and not on physical principles alone.

9.4 Biology: The Motion of the Heart and Blood

Whether William Harvey knew Galileo personally is not known, but the two were contemporaries at the University of Padua, where Harvey was awarded the doctorate in 1602 as completely qualified in both arts and medicine. Like Galileo, Harvey employed the methodology of the *Posterior Analytics* in his scientific researches, although unlike him, he did so explicitly and with repeated acknowledgment that Aristotle was guiding his investigations. This is apparent in both of his anatomical classics, *On the Motion of the Heart and Blood in Animals* and *On the Generation of Animals*. The first of these was composed when Harvey was about fifty years old and the second twenty-three years later—showing how unvarying he was, even in his last years, on the methodology he followed.

The greater part of *On the Motion of the Heart and Blood* is directed toward establishing a scientific demonstration of the circulation of the blood. Although not published until 1628, the essential elements of the demonstration were already present in notes composed by Harvey for a series of lectures given at the Royal College of Physicians in London in 1616. Both in these lectures and in the published work he argued against a teaching deriving from Galen that was deeply entrenched and commonly entertained in his day. This was that blood in animals is produced in a central organ within the body and then distributed to the extremities, being gradually absorbed in the process. Working before the discovery of the microscope, and thus unable to trace the complete course of the blood's movement, Harvey nonetheless was able to demonstrate from valve action and from the quantity of blood contained within the body that continuous motion in a circle is the only way to account for the blood's flow. From this conclusion he was led to investigate the causes of this circulation and thus to connect the flow of blood with the pumping action of the heart.

The first part of the treatise consists in an extended observational analysis of the motion of the cardiovascular system, based on the dissection of living animals. Harvey gave attention successively to the motion of what he calls "the containing parts," that is, the arteries and the heart, and to that of "the contained part," the blood, with particular reference to the ventricles of the heart and the passage through the lungs. What impressed him from these observations is the huge quantity of blood that passes through the heart in a very short period of time, much more than the digestive system can continue to produce. He then began to suspect that such an abundance of blood passing from the heart out of the veins into the arteries can be accounted for in only one way, namely, by a circulatory motion on the part of the blood. He arrived at this conclusion, as he explains it, in the following way:

> . . . When I surveyed my mass of evidence, . . . I frequently and seriously bethought me, and long revolved in my mind, what might be the quantity of blood which was transmitted, in how short a time its passage might be effected, and the like. And not finding it possible that this could be supplied by the juices of the ingested aliment. . . unless the blood should somehow find its way from the arteries into the veins, and so return to the right side of the heart, I began to think whether there might not be a *a motion, as it were, in a circle.* Now this I afterwards found to be true . . .[18]

Once Harvey had hit upon this insight he saw immediately why, in dead animals, a large quantity of blood is found in the veins and very little in the arteries. The "true cause" of this, he argued, is that there is no passage to the arteries except through the lungs and the heart. Thus, when the animal ceases to breathe, the source of blood to the arteries is cut off, though the heart pulsates for a time and causes blood to accumulate in the veins. Harvey then repeated experiments that had been performed by his teacher Fabricius of Aquapendente, who had applied ligatures to the arm of a living man, and found that the results obtained

18. *The Works of William Harvey, M.D.*, trans. Robert Willis, London: Sydenham Society, 1847, pp. 45–46.

could be explained in the same way. These arguments led him to the inexorable conclusion, established by both "argument and ocular demonstration," that the blood passes through the lungs and heart by the action of the heart's auricles and ventricals. It is there sent for distribution to all parts of the body, where it makes its way into the veins and pores of the flesh, then flows back through the veins, and is finally discharged by them into the vena cava and right auricle of the heart. The discharge is in such quantity that it cannot possible be supplied by the ingesta, he noted, and is much greater than can be required for mere purposes of nutrition.[19]

To sum it all up in no uncertain terms, Harvey wrote,

> *It is absolutely necessary to conclude* that the blood in the animal body is impelled in a circle, and is in a state of ceaseless motion; that this is the act or function which the heart performs by means of the pulse, and that *it is the sole and only end* of the motion and contraction of the heart.[20]

With regard to the motion and function of the heart, there is no doubt that Harvey was convinced he had secured a strict demonstration according to the canons of the *Posterior Analytics*. Since his technique was also that of the Paduan *regressus*, it is possible to reformulate his proof using the same schema we have used for Galileo's demonstrations in the previous two sections. Like Galileo, Harvey made use of suppositions, but unlike Galileo he took great pains to establish the truth of his suppositions as he proceeded along with his argument. This becomes clear in the intermediate stage of the regress, as shown below:

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.***

Effect	**Cause**
a fluid of limited quantity that is kept in constant motion in one direction	moves in such a way that it returns repeatedly over the same path and so flows in a circle

Intermediate stage: ***work of the intellect, testing to see of this is a cause convertible with the effect, eliminating other possibilities.***

Dissection and ocular demonstration: Contrary to Galen's expectations, the heart and the arteries in the living animal always contain blood. The proper motion of the heart is contraction, not expansion. The heart's action is pump-like, not bellows-like, and it forcibly expels blood in one direction only. The heart's contraction (systole), not its expansion (diastole), corre-

19. Ibid., pp. 51–68.

20. Ibid., p. 68, italics added.

sponds to the pulse in the chest wall. The pulse in the arteries, when in diastole, corresponds to the heart's systole (not to its diastole)—as shown by experiments on cold-blooded animals and on warm-blooded animals when near death, as their heartbeat slows. The cardiac systole is the cause of the arterial pulse via the motion it transmits through the blood. And the blood from the right ventricle of the heart reaches the left ventrical through the lungs.

Logical analysis: *Supposition 1*: The blood is continually transmitted by the action of the heart from the vena cava to the arteries in such quantities that it cannot be supplied by the ingesta, and in such wise that the entire mass must pass very quickly through the heart. *Confirmation*: by measurements of the actual quantity of blood transported in various units of time.

Supposition 2: Under the influence of the arterial pulse the blood enters and is impelled in a continuous and uniform stream throughout the body, in much larger quantity than suffices for nutrition or than the whole mass of fluids can supply. *Confirmation*: by ingenious experiments using ligatures. (These were necessary since the return flow is through capillaries too small to be seen with the unaided eye; Malphigi first observed this flow in 1661 with a microscope, thus confirming Harvey's finding.)

Supposition 3: The veins in like manner return this blood continuously to the heart from all parts and members of the body. *Confirmation*: from an examination of the valves found in the cavities of the veins themselves, and testing this with ligatures and with pressure exerted by the finger applied at various points along the vein.

Second progression: ***from the cause, recognized formally as the cause, to its proper effects.***

Cause	Effect
the pumping action of the heart, impelling the blood in a circle through the lungs and through the arteries and the veins	explains the phenomena of the pulse and how a limited quantity of blood can be kept in constant motion throughout the body.

Having thus concluded apodictically that the fact of the blood's circulation cannot be other than it is, Harvey devotes the remaining chapters of his treatise to various *a posteriori* proofs and confirmatory arguments. His final chapter serves as a summary and synthetic exposition of the definition of the heart, touching on all four of its causes, namely: its formal cause, the anatomical structure described in terms of its function; its material cause, the muscular and other tissue sustaining this structure and operation; its final cause, the circulation of the blood; and the efficient cause of the circulation, the contraction whereby the heart fulfills its function. Having explained all this in detail, Harvey concludes his treatise simply with the words, "It would be difficult to explain in any other way for what cause all is constructed and arranged as we have seen it to be."[21]

The definition of the heart may be arranged in syllogistic form, in much the same way as the definition of the rainbow was presented above in Section 9.1, as follows:[22]

S	M	P
[1] The heart		
	[2] is an organ which must supply the body with a steady flow of a fluid whose quantity is proportionately small	
		[3] is an organ which is so constructed as to produce a circular motion in that fluid; that is
		[4] an organ which has a pulsating left ventricle with a non-regurgitating valvular inlet and outlet and additional cardiac parts that conform to the needs of the species, e.g., the arrangement of the fibres in the walls, the valves, and the braces of the heart;
		[5] and is composed of muscular tissue and other tissue components necessary to these parts;
		[6] for the sake of circulating the blood,
		[7] by a rhythmic and periodic contraction.

In this schematic arrangement [1] is obviously the subject, the heart, and [2] the middle term, which characterizes the main function of the heart in the animal body. The predicate [3] provides a general anatomical description of the organ, which is spelled out in fuller detail in the remaining causal predicates: [4] presents the formal cause, the anatomical structure described teleologically and in relation to the motion of the heart, the pulse, etc.; [5] identifies the material cause, the types of tissue required in an organ of this type; [6] specifies the final cause or function of the organ; and [7] the precise efficient cause of the circulation, the

21. Ibid., reading "cause" for "purpose" in Willis's translation of Harvey's *quam ob causam.*

22. Adapted from Herbert A. Ratner, "William Harvey, M.D.: Modern or Ancient Scientist?," *The Dignity of Science: Studies in the Philosophy of Science*, ed. J. A. Weisheipl, Washington, D.C.: The Thomist Press, 1961, pp. 67–68; the essay appeared originally in *The Thomist,* 24 (1961), pp. 175–208.

motion it proximately produces. Notice here that the individual causes now appear as predicate terms, whereas in the demonstration of the rainbow's properties the causes appeared as middle terms. This inversion signals that the definition of the heart is reached by *a posteriori* reasoning from a particular effect, namely, a quantitative modality of the flow of blood, to the causal factors required to produce it. The properties of rainbow, on the other hand, were detailed by *a priori* reasoning, arguing from the quantitative modalities of causes that produce the bow to the various geometrical properties it exhibits when seen in the heavens.

9.5 Optics: Light and Color

Theodoric of Freiberg's demonstration of the rainbow's properties was completed by 1311 and the manuscript containing it was subsequently copied a number of times. It did not appear in print for another two hundred years, however, when it was reproduced by Jodocus Trutfetter of Eisenach in his *Summa in totam physicam, hoc est, philosophiam naturalem*, published at Erfurt in 1514 and again in 1517. Trutfetter identified Theodoric as his source and illustrated his teaching with woodcuts showing the paths of light rays through raindrops diagrammed above in Figs. 9.1 through 9.5. After that, the explanation was lost again, not to be recovered until René Descartes published it in his *Les Météores* of 1637. Descartes concealed his sources, as was his custom, but parallel passages suggest a heavy dependence on Theodoric. Particularly revealing is the diagram Descartes used to accompany his explanation. This is reproduced in Fig. 9.7, which shows paths of the light rays that are almost identical to those in Theodoric's manuscripts.[23]

Descartes' treatment of the formation of the bow is considerably briefer than Theodoric's, but it does correct the error the latter gives for the angle the primary rainbow makes with the eye. Descartes was also more precise and detailed in his measurement of the various angles of refraction. He observed, for example, that the rays producing the primary bow are seen at angles between approximately 42° (red) and 41° (blue) from the incident light, and the rays producing the secondary bow between approximately 51° (red) and 52° (blue). Beyond this, he calcu-

23. For details, see *The Scientific Methodology of Theodoric of Freiberg*, pp. 254–263. The diagram is reproduced from Descartes' *Discours de la Méthode, la Dioptrique, les Météores, et la Géométrie*, first published in 1637. A similar illustration is found in Isaac Newton's *Opticks*, 4th ed., London 1730, rept. New York: Dover Publications, 1952, p. 173.

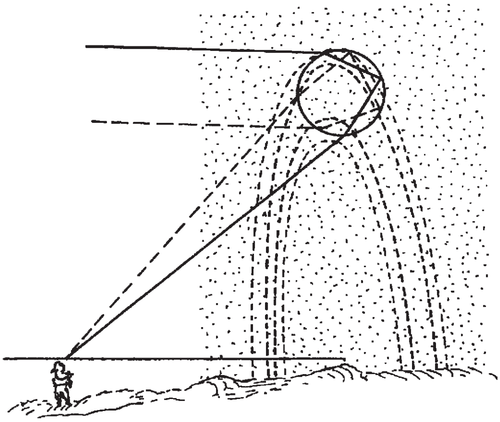

Fig. 9.7 Descartes' Diagram for the Primary and Secondary Rainbow

lated, by means of the newly formulated law of refraction, a table of angles of deviation for different angles of incidence from a spherical drop, and pointed out that there was an angle of minimum deviation at which the rays emerge almost parallel, and therefore reach the eye of the observer in the greatest concentration. His calculations show that in the case of the red rays this angle will be 41° 47' for the primary bow and 51° 37' for the secondary.[24]

Descartes also made an attempt to explain how the colors of the rainbow are generated in terms of the motion of hypothetical light particles that transmit its appearance to the eye. This turned out to be valueless, but it seems to have yielded at least one positive result. It stimulated Sir Isaac Newton, while still a student at Cambridge, to begin experiments with the spectrum that would eventually produce a "New Theory about Light and Colors." This appeared in the form of a letter to the Royal Society that was printed in its *Philosophical Transactions* of 1671/1672. In the letter Newton describes his discoveries and experiments as having taken place in a simple chronological sequence during the year 1666, while he was at home during an outbreak of the plague at Cambridge. There are indications, however, that the account is not as chronological as he presents it, but is actually a methodological reconstruction designed to show that the argument he presents is not a mere hypothesis, as was Descartes'. Rather it was a physico-mathematical demonstration

24. Ibid., pp. 258–259.

based on observation and experiment that concludes, as he claims, "without any suspicion of doubt."[25]

Newton's account of the discovery begins with his observation of a peculiarity in the shape of the spectrum that results when a beam of sunlight passes through a prism and is projected on a wall in a darkened chamber, as shown in Fig. 9.8. What caught his attention was the fact that the circular beam, which he thought should project an orbicular image, assumed an oblong form whose length was five times greater than its breadth. Acquainted as Newton was with the various mechanistic theories of light then current, he tried to account for the elongation of the image in terms of explanations such theories might afford. Perhaps the shape of the spectrum was explicable in terms of the thickness of the prism or the size of the aperture through which the circular beam of sunlight was initially admitted to it. Another possibility was that the disproportionate length of the image could be caused by some unevenness or irregularity in the glass of the prism. Yet another was that light might be composed of small particles that rotate, along the lines of Descartes' conception, and that their spinning motions might cause them to travel in lines of varying curvature and thus distend the image they produce.

Each of these hypotheses Newton considered in turn and falsified by a series of remarkable experiments. Having done this, he began to speculate as to what the "true cause" of the image's elongation might be. This led him to what he calls his *experimentum crucis*, diagrammed in Fig. 9.9. In it two prisms are set up in such a way that one can control a particular ray of light passing through the second prism and see what the re-

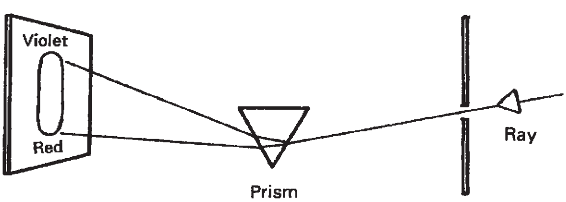

Fig. 9.8 Newton's One-Prism Experiment

25. *The Correspondence of Isaac Newton*, ed. H. W. Turnbull, vol. 1, Cambridge: Cambridge University Press, 1959, pp. 96–97; *Philosophical Transactions* 80 (1671–1672), pp. 3075–3079.

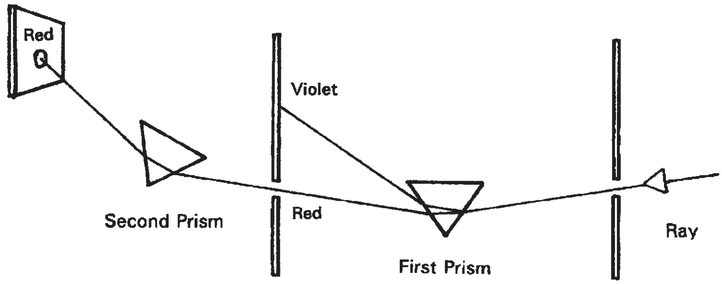

Fig. 9.9 Newton's *Experimentum crucis*

lationship might be between the color of the ray and the angle at which it is refracted. He performed the experiment and noted that the red rays at the end of the spectrum are refracted very little, whereas the violet rays at the opposite end undergo a considerable refraction. Noting this difference, Newton saw in it the proper cause that explains why the image is elongated, and concluded immediately:

> And so the true cause of the length of that image was detected to be no other, than that light consists of rays differently refrangible, which, without any respect to a difference in their incidence, were, according to their degrees of refrangibility, transmitted towards divers parts of the wall.[26]

Thus the conclusion of the *experimentum crucis* is that sunlight or white light is composed of different rays that are refractible in varying degrees, and that the resolution of the white light into its various components by the prism is the unique cause of the elongation of the image projected on the wall.

A methodological analysis of the brief passage in which Newton describes his discovery shows that he actually used a twofold process of resolution and composition, or, as he calls it in his later writings, analysis and synthesis.[27] This is the same as the demonstrative *regressus* employed by Galileo. Rather than present the argument in that form, however, we here formulate the two syllogisms that are implicit in Newton's account, the first *a posteriori*, from effect to cause, and the second *a priori*, from cause to effect. The resolutive process leads to what he identifies as the "true cause" of the length of the image, and goes as follows:

26. *Philosophical Transactions*, 80 (1671–1672), p. 3079.
27. Particularly in his *Opticks*, Bk. 3, Part 1, ed. cited, pp. 404–405.

S	M	P
The light of the sun, or white light,		
	is light which, when passed through two prisms separated by a collimator, upon the gradual rotation of the first prism is found to produce from the second prism images of different colors that successively occupy all the positions collectively occupied by the elongated image	
		is composed of difform colored rays, some of which are more refrangible than others.

The composite process then takes this cause and returns to the order of sense experience, thus showing how the cause produces the observed effect:

The light of the sun, or white light		
	is light composed of difform colored rays, some of which are more refrangible than others	
		is transmitted through a prism refracted at various angles so as to produce an elongated multi-colored image on the wall.

Convincing as this exposition seems to be, the various reactions that were evoked by the publication of Newton's paper in the *Philosophical Transactions* were decidedly negative, so much so that they almost dissuaded him, at the outset of his career, from publishing any more of his scientific discoveries. Some of the non-acceptance was caused by the inability of his readers to duplicate the *experimentum crucis* and verify its results. More widespread was the seeming inability of scientists in Newton's day to comprehend the method he had used to establish his results. The problematic that resulted from this situation will be discussed in the following chapter.

9.6 Dynamics: Universal Gravitation

A yet more fascinating study of Newton's scientific work is the development of his thought on the nature and cause of gravity, a topic about which he speculated much, and where his conclusions bear a striking resemblance to those just seen in relation to light and color. Since space does not permit a detailed presentation, we here limit ourselves to summary remarks based on the second edition of his *Mathematical Princi-*

ples of Natural Philosophy, published at Cambridge in 1713. This is a systematic treatise in the style of Euclid and Archimedes, beginning with various definitions and the three axioms or laws of motion on which the remainder of the development rests. It is then divided into three books, the first of which treats the motion of bodies in empty space, the second the motion of bodies in resistive media, and the third the system of the world. Although the subject of gravitational attraction is touched on occasionally in the first two books, it is not treated *ex professo* until the third book, which will be the main focus of attention in what follows. Only this book, strictly speaking, is mathematical physics; the other two develop geometrical propositions using the laws of motion and limit concepts to provide an idealized dynamical system that may be applied to the physical world.

In the first book Newton derives his mathematical formulation of the inverse square law of gravitational attraction by first considering the "one-body" problem. He considers the path of a body initially in uniform rectilinear motion and then acted on by a force directing it to a point or center external to its line of motion. He finds that, if this center-seeking force varies inversely as the square of the distance from the center, the body will sweep out equal areas in equal intervals of time with respect to that center. Moreover, depending on the velocity of the motion, the body will follow a path around the center that is one of the conic sections, namely, an ellipse, a parabola, or a hyperbola. From this Newton moves to the "two-body" problem, considering the motion of two bodies tending toward a common center, and thus "attracting" each other. ("Attracting" here is not to be understood "physically," Newton cautions, but only "mathematically," for in this way he can make himself "more easily understood by a mathematical reader.") He then finds not only that both bodies describe conic sections around their common center of gravity and around each other, but that the equal centripetal forces acting on each are inversely proportional to the squares of their distances from the center.

With this as essential background, Newton begins his third book with his *Regulae philosophandi* or Rules of Philosophizing, which lay out the methodology he will employ in applying these propositions to the physical world. The rules read as follows:

> 1. We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances. . . .
>
> 2. Therefore to the same natural effects we must, as far as possible, assign the same causes. . . .

3. The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever. . . .

4. In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwitstanding any contrary hypothesis that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions. . . .

Obviously Newton here conceives scientific method as essentially a search for causes. He also presupposes that there is uniformity in nature, so that he can employ inductive argument and generalize on the basis of causal reasoning, plus limited and careful observation and experimentation. This would seem to cover the substance of his first, second, and fourth rules.

The third rule then carries the heavy baggage for the entire third book. In explaining the rule Newton first supplies a few simple examples of how sense knowledge provides the basis for our assigning attributes such as extension, impenetrability, mobility, and inertia to *all* bodies, despite the fact that only a *few* bodies fall under our experience. The process whereby we arrive at such generalizations, he states, "is the foundation of all philosophy." Newton then cites the experimental evidence that has led him to the law of universal gravitation. The empirical data of astronomy show that a uniformly accelerated type of motion does actually occur in the heavens, and this further reveals that celestial matter is no different from terrestrial matter in that both matters undergo a "falling" motion. Stated otherwise, all observable bodies gravitate, and thus are endowed with a gravitational principle. Or again, all bodies that are observable in the universe, on earth and in the heavens, have gravity, or are heavy. What Newton is here implying is that one can no longer maintain that some bodies are essentially light or composed of a quintessence whose natural motion is eternally circular. He realizes that his evidence for this momentous conclusion is not overwhelming, and yet he believes it to be sufficient in light of his third rule. So he concludes, "If it universally appears, by experiments and astronomical observations," that all bodies we can see gravitate, "we must, in consequence of this rule, universally allow that all bodies whatsoever are endowed with a principle of mutual gravitation."

Actually an *a posteriori* demonstration is implicit in the remarks Newton appends to his third rule of philosophizing, which may be formulated as follows:

S	M	P
All bodies that can be observed on earth or in the heavens		
	move toward a center or follow paths of conic sections around a center as they are urged by a force inversely proportional to the square of their distance from that center	
		are endowed with a principle of mutual gravitation, or gravitate, or are heavy, ponderous bodies.

Here the middle term is an effect, a quantitative modality in the natural motions of all bodies whenever such motions are measured directly or indirectly, and the predicate term is a proper cause, namely, the power of gravity with which these bodies are endowed.

Newton's reasoning with regard to gravity bears a significant resemblance to his reasoning concerning the cause of the elongation of the prism's image that led to his new theory of light and color. He also followed essentially the same method as Galileo used in the demonstrative *regressus* described in Secs. 9.2 and 9.3 above. This can be seen from the following schema, which summarizes the main argument in Book III of the *Principia* in three stages analogous to those earlier used by Galileo:[28]

Resolution: ***from the observation of a peculiar effect to speculation about what might be its true cause.***

Effect	**Cause**
the ways in which bodies on earth, planets and their satellites, comets, and the earth's seas move	suggests that their motions are all reducible to the same cause, the attractive force of gravity

Observational-experimental stage: ***detailed observations and measurements that reveal the common features of these motions, leading to a common cause—in light of the stated "rules of philosophizing."***

Phenomena: 1. The satellites of Jupiter describe areas proportional to their periodic times, which are as the 3/2th power of their distances from Jupiter.

2. The satellites of Saturn [do the same] with respect to Saturn.

3. The five primary planets (Mercury, Venus, Mars, Jupiter, and Saturn) [do the same] with respect to the sun.

28. Adapted from the points William Whewell lists in the "Inductive Table of Astronomy" he appends to his *Philosophy of the Inductive Sciences* as having been established by Newton in the *Principia*.

4. The moon [does the same] with respect to the earth.

Propositions: 1. The forces acting on the satellites of Jupiter vary inversely as the square of their distances from Jupiter, from Book I and Kepler's laws of planetary motion.

2. The forces acting on the primary planets [do the same] from the sun.

3. The forces acting on the moon [do the same] from the earth.

4. The moon gravitates toward the earth . . .

5. The satellites of the planets gravitate toward their respective planets.

6. All bodies gravitate toward every planet . . .

7. Parts of the earth gravitate toward other parts.

8. The oceans of the earth gravitate toward the moon and the sun, producing the tides.

9. The equatorial bulge of the earth as an oblate spheroid gravitates toward the sun and the moon, producing the precession of the equinoxes.

10. There is a power of gravity pertaining to all bodies, proportional to the several quantities of matter which they contain, and varying inversely as the square of the distances between their centers.

Composition: ***the cause that has been ascertained, the universal power of gravity, explains all of the known phenomena.***

Cause	Effect
Universal gravitation, or the power of gravity found in all bodies on the earth or in the solar system	explains all of the observed natural motions of the earth, the moon, the sun, the planets,and comets, and of bodies and seas on the earth's surface

On the basis of this line of reasoning, Newton was convinced that gravity is physical and real, existing in the planets and their satellites as well as in the earth, moon and sun, all of which are endowed with a gravitational principle. Thus the moon is maintained in its elliptical motion around the earth by two forces, one deriving from its inertia, which urges it to fly off into space tangentially in a straight line, and the other deriving from its gravity, which urges it toward the earth by centripetal attraction of some form or another. Newton reasoned that if the moon's motion is real, and if the momentum that would carry it off into space is real, then its gravity must be real also. He thus had no doubt that gravity is the "true cause" of the moon's "falling motion" toward the earth, just as white light's composition of difform rays is the "true cause" of the elongation of the spectrum. But, just as the latter conclusion was called into question by his many critics after the publication of his letter to the *Philosophical Transactions*, so the former was quickly called into question soon after the publication of the *Principia*. Again, we postpone our consideration of the controversy that ensued to the following chapter.

9.7 Chemistry: Atoms and Molecules

Newton was truly ingenious in the way he was able to make the science of light and color "become mathematical," as he claimed in his covering letter to the editor of the *Transactions*. He was even more ingenious in the indirect methods he devised to measure the various motions on earth and in the solar system cited in the *Principia* (phenomena 1–4, propositions 1–3, above) and thus to quantify gravity and its effects. But, despite the fact that he was truly convinced that macroscopic bodies are composed of minute particles, he himself was unable to extend the methods that were successful in the *Principia*, and later in his *Opticks*, to the study of the microstructure of matter. Yet Newton's writings stimulated others to do so, and many attempts were made in the century that followed to make chemistry truly a quantitative science. It was not until the nineteenth century that substantial progress was made in this endeavor. And when it was, it was not through the application of the geometrical principles that worked so well for Theodoric of Freiberg, Galileo, and Newton, but rather through the use of conservation principles and simple arithmetical calculations of the type employed by William Harvey. The basic idea goes back to Aristotle's teaching that the unit is the principle of number. How this idea was applied by various investigators to uncover the various "units" involved in chemical phenomena, and ultimately in all "quantum" phenomena, is the project to be sketched in this section.

The persons who figure most importantly in this quest are two Frenchmen, Antoine Lavoisier (1743–1794) and Joseph Gay-Lussac (1778–1850), an Englishman, John Dalton (1766–1844), and two Italians, Amedeo Avogadro (1776–1856) and Stanislao Cannizzaro (1826–1910). The nationalities are important, because differences in language and in respective cultural and ethnic affiiliations impeded the understanding and assimilation of important contributions in the sequence in which they were made. It seems particularly unfortunate that the findings of Gay-Lussac and Avogadro were not grasped by many chemists, particularly those working in England and Germany.

Lavoisier is commonly regarded as the founder of modern chemistry, mainly because he coined many of the names by which chemical elements are known to the present day. Building on the work of Joseph Black, Joseph Priestley, and Henry Cavendish in Britain, Lavoisier made precise measurements of the weights of the reagents involved in chemical reactions. Using the principle that weight is conserved in such reactions, he was able to dispel a notion common among phlogiston chemists, namely, that heating or combustion is a process of analysis whereby weight is driven off by fire. He showed, to the contrary, that substances can gain weight on heating, and thus that combustion can also be a process of synthesis. Through a series of precise measurements he was further able to show that air is not an element, but is itself composed of various components. These he identified as pure air, noxious air, fixed air, and inflammable air—identified as oxygen, nitrogen, carbon dioxide, and hydrogen respectively.

The Greek concept of atom, revived by Pierre Gassendi in the seventeenth century, gained currency through the endorsement of Robert Boyle, Newton, and others, but it had no quantitative significance until the work of John Dalton in the first decade of the nineteenth century. Investigating the physical properties of gases, Dalton advanced the idea that the chemical elements are composed of small indivisible particles called atoms that maintain their individuality in chemical reactions. He further maintained that all atoms of a particular element are identical and have the same weight, but that the atoms of other elements have different weights, each of which is characteristic of the particular element. Through a series of experiments and measurements, he was able to formulate the law of combining weights and the laws of constant, multiple, and equivalent proportions as well. One of his important findings was that water is a binary compound formed from an atom of hydrogen and an atom of oxygen, in the approximate ratio of one to seven by weight. He also published in 1808 a table of atomic weights consisting of twenty elements and various compounds he thought would result from their combination in different proportions.

In the same year Gay-Lussac, making volumetric measurements of gases entering into chemical combination, enunciated the law of combining volumes. He was able to confirm that hydrogen and oxygen combine by volume in the ratio of two hundred to one hundred to form water. He also regarded his ratios as more precise than those of Dalton, who argued, as already noted, that hydrogen and oxygen combine by weight in the ratio of seven to one to form the same compound. Dalton, in his turn, refused to accept Gay-Lussac's law, and this led to an impasse between the English and the French on the exact quantities of hydrogen and oxygen that combine to form water. A way out of the impasse was worked out in 1811 by Avogadro, working at Turin in northern Italy. But his results went virtually unnoticed for almost half a century, thus unfortunately slowing the growth of the science of chemistry.

Part of the difficulty stemmed from Avogadro's use of the term molecule (meaning "small mass") rather than the term atom (meaning "indivisible") to designate the smallest part of an element that enters into chemical combination. The solution he proposed made use of what is known as "Avogradro's hypothesis"; this states that equal volumes of different gases contain the same number of ultimate particles under the same conditions of pressure and temperature. Applying that hypothesis to the dispute between Dalton and Gay-Lussac, Avogadro reasoned that molecules were the smallest parts of a gas that occur in its free state, but that half molecules are the units that enter into chemical combination. His "half molecules" here become the equivalent of Dalton's atoms. Thus, in his proposal, Avogadro had adumbrated the distinction between atoms and molecules. To use modern chemical notation, Avogadro was able to show that Dalton, using measurements of weight, had come to the conclusion that $H + O \rightarrow HO$, whereas Gay-Lussac, using measurements of volume, had come to the conclusion that $2H + O \rightarrow HO$. In a sense, both are right if the letters H and O are used to designate molecules, and yet both were unaware of the fact that "half molecules" (read atoms) are actually involved in the reaction. When these are taken into account, the correct formula comes out to be $2H_2 + 1O_2 \rightarrow 2H_2O$, where the prefixed numerals designate the number of molecules and the subscripts the numbers of atoms that combine to form each molecule.

It seems that, although many chemists were working on the problem of chemical weights in the first half of the nineteenth century, by and large they were unaware of, or failed to understand, the investigations of Avogadro and Gay-Lussac. But one of Avogadro's countrymen working at the University of Genoa, Cannizzaro, after years of teaching the basic concepts of chemistry and their historical development, succeeded in clarifying the distinction between atoms and molecules in terms that his contemporaries could understand. He presented his analysis at the first international chemical conference at Karlsruhe, Germany, in 1860. Although his oral presentation there was unsuccessful, his associate Angelo Pavesi distributed to those in attendance an abridgment of Cannizzaro's notes for the course in chemistry he taught at Genoa. Lothar Meyer, among others, was most impressed by these notes for the course, and went on to incorporate Cannizzaro's teachings on atoms, molecules, atomic weights, and molecular weights in his textbook, *Modernen Theorie der Chemie*, which appeared in 1864. The most important point was to set the atomic weight of hydrogen at unity and then extract the relative atomic weights of the remaining elements from the confusing mass of molecular weights that had been accumulating over the decades. From this quickly followed the correct way to write chemical formulae, and, ultimately, the way to arrange all of the elements in the order of their ascending atomic weights, while showing the periodicity of their properties, in what is now known as the periodic table.

Cannizzaro's reasoning in the course abridgement distributed at Karlsruhe implicitly contains a demonstrative syllogism, which may be formulated as follows:[29]

S	M	P
The relative weight of a chemical compound		
	is the sum of relative weights combined in integral and fixed proportions by weight	
		is caused by composite particles of integral combined weight (called "molecules"), whose components are simple particles of unit relative weight (called "atoms")

In the terms of this syllogism, "weight" may be replaced by "mass" to conform to later usage, but this change is not essential to grasping the force of the argument. The minor premise, S-M, is a physical premise that summarizes all of the experimental data amassed from Dalton's time to Cannizzaro's and formulated variously as the laws of combining weights, combining volumes, constant proportions, multiple proportions, equivalent proportions, etc. It is established by induction from repeated measurements, and these using a variety of techniques. The major premise, M-P, is a mathematical premise, and it is grasped intuitively from the fact that the unit is the principle of number. All of the devices used to measure weights are in principle continuously variable, and yet discrete or integral values continue to turn up in the measurements. Whence does the discontinuity arise? This results, not from the measurer, but from the object being measured. There must be a cause in nature that produces discrete effects, and this turns out to be twofold: the molecule, which is the natural minimum of the chemical compound, and the atom, the natural minimum of the chemical element. The fact that two causes are here involved posed the difficulty that blocked the progress of chemistry for the half century separating the work of Avogadro from that of Cannizzaro.

The demonstration is *a posteriori*, from effect to cause, and it merely

29. For a fuller explanation of this type of demonstration, see my "The Reality of Elementary Particles," reprinted in *From a Realist Point of View*, 2d ed., pp. 171–183.

concludes to the existence of atoms and molecules without stating *what* they might be, apart from their being integral parts of the bodies that come under sense experience. The problem here is complicated by the fact that the data are gathered from a study of chemical reactions involving natural generations. As explained in Sec. 2.6, the conservation of mass or mass-energy is presupposed in these calculations, and to the extent that it is, the demonstration is made *ex suppositione*, on the supposition of mass-energy conservation. Apart from this, theoretical considerations do not enter into, or affect, the quantitative evidence adduced in support of the demonstration. One need not subscribe to any particular view of the structure of matter, whether matter is a wave or a particle, what shapes the element assumes in the compound, and so on. Nor need one be concerned about weight or mass, and particularly the latter, which is part of a theoretical system of mechanics that is not capable of direct experimental confirmation and thus is itself a theoretical concept. Whatever the ontological status of mass conceived in this way, since it is always employed in a univocal sense as a unit of measurement, and since this unit cancels out when measurements are placed in ratios to obtain relative magnitudes, the theoretical interpretation one places on the unit is irrelevant to the argumentation. The reasoning process thus leads to the inescapable conclusion that a unit mass detected in the laboratory has some counterpart in the order of nature. The unit mass does not exist in the mind of the experimenter alone, but exists in some way outside the mind. And therefore the entity that possesses the unit mass, or to which the unit mass is ascribed, also enjoys an extramental existence.

Similar modes of argument can be applied to other experimental data that show stepwise characteristics and thus point to *quanta* or discrete intervals in the measurement of quantities apart from weight or mass.[30] One of the simplest cases is that involving the unit of electric charge. This was suspected by a number of investigators and was finally confirmed by Robert A. Millikan early in the twentieth century, from his measurement of minute charges that accumulate on small oil drops. From a series of precise measurements in what are called the oil-drop experiments, Millikan discovered that the charges on the drops were always some integral multiple of a very small unit, which he identified with the electron. His reasoning went as follows:

30. This line of argument is pursued in my "Elementarity and Reality in Particle Physics," *Boston Studies in the Philosophy of Science* 3 (1968), pp. 236–271; reprinted in *From a Realist Point of View*, 2d ed., pp. 185–212.

S	M	P
The electric charge on a minute oil drop		
	is a charge that varies in discrete integral steps from a minimum value	
		is caused by unit electric charges (called "electrons")

The reasoning here is less complicated than that establishing the existence of atoms and molecules, since in the latter case two unit values were involved rather than one. But the basic principle is the same: the unit is the principle of discrete, positive integers. The conclusion thus follows that a unit electric charge exists, and therefore that an entity corresponding to this charge, which had already been named the electron by George J. Stoney in 1881, exists also.

This general line of reasoning has been exploited throughout the twentieth century and has let to the discovery of all the so-called "particles" of modern physics: the photon, the positron, the proton and the neutron, mesons, quarks, and so on. Measurements far more precise than those available to Cannizzaro, who already knew of isomers, that is, molecules with the same chemical formula but different structural arrangements, led around 1910 to the identification of isotopes—elements occupying the same place in the periodic table, but having different numbers of neutrons in their nuclei. These and other refinements led to a fuller understanding of atoms and molecules, and resulted in an unprecedented expansion of the science of chemistry throughout the twentieth century. Along with this they also posed theoretical problems relating to the ultimate structure of matter, including the quantum anomalies that have become a main concern for philosophers of science in the present day.

9.8 Biochemistry: The DNA Molecule

A final case study that, like the others, does not require sophisticated mathematics for its understanding is the discovery of the structure of the DNA molecule in 1953. The "quantum-jump" principle that functioned throughout the previous section did not figure in that discovery, but another type of reasoning that has frequently been employed throughout this chapter did. This type involves the use of projective geometry to analyze a quantitative modification in a sensible appearance and then to arrive at a proportionate cause that alone can serve to explain it. Light rays were the previous means used to investigate the shape of the moon and mountains on its surface, the phases of Venus, the satellites of Jupiter, and the elongation of the spectrum. For the discovery to be discussed in this section a different form of electromagnetic radiation was used, namely, x-rays.

As mentioned in Sec. 2.3, working in the second decade of the twentieth century Max von Laue had discovered the lattice structure of crystals through a study of the diffraction patterns produced when x-rays are passed through a crystal such as common salt. The molecule of salt, NaCl, has a simple structure and takes on a cubic form when it crystallizes. Now the very large molecules involved in life processes, the megamolecules that have been discussed in Secs. 3.2 and 3.3, assume forms far more complex than that of a cubical crystal. But they too have distinctive diffraction patterns when subjected to radiation in the x-ray region of the spectrum. The field of study that analyzes these patterns to detect the three-dimensional structures that produce them is known as x-ray crystallography. The data are so complex that they require powerful computers to carry out the numerical computations needed to determine the underlying structures. But, once determined, the structures themselves are picturable and readily grasped by those with only an amateur interest in science. That perhaps explains why molecular biology has such appeal to nonspecialists and has so captured the popular imagination in the present day.[31]

The actual discovery of DNA's structure came very quickly after the basic foundations had been laid in organic chemistry and x-ray crystallography. Like the protein molecules mentioned in Sec. 3.2, nucleic acids are very large molecules, often much larger than proteins. They are also, like the proteins, long chain molecules that are difficult to handle and analyze. Their chemical composition was first investigated by Phoebus Levene, who found in 1909 that nucleic acids contain a sugar, ribose. In 1929, he found them in another, previously unknown sugar, dioxyribose. The latter enters into the chains that make up the DNA molecule, which are tied together by the bases mentioned in Sec. 3.3. These bases were found to be of four types, adenine, guanine, cytosine, and thymine, usually abbreviated by their first letters, A, G, C, and T. At first it was thought that all four were found in equal quantities in the mole-

31. This point is made by John Kendrew in the preface to his *The Thread of Life: An Introduction to Molecular Biology*, which grew out of a series of B.B.C. television lectures of the same title. The book provides an excellent introduction to techniques of x-ray crystallography, along with the background necessary to understand Crick and Watson's work on the DNA molecule.

cule, repeating in an unvarying sequence along the chains. Late in the 1940s, however, Erwin Chargaff was able to obtain pure samples of DNA and carried out accurate analyses of the proportions of the bases in his specimens. He found that in general the percentages of bases were far from equal, varying widely from one specimen to the other. But an equality did manifest itself in the pairings of the bases: whatever the proportions turned out to be, the amount of A always equalled that of T, and the amount of G that of C. Now the A's and G's are large bases, and the T's and C's small bases, so that equalities of large and small bases enter consistently into the structure of the molecule. The generalization was noted, but its significance was not perceived at that time.

Meanwhile, advances were being made in x-ray crystallography. In the 1930s, W. T. Astbury made x-ray diffraction patterns of human hair, and then in 1937 discovered that a wool thread yields a different pattern when it is stretched than when it is not. In both cases the patterns gave indication that the molecules of hair and thread are arranged in an orderly sequence. The x-rays were rather diffuse, however, and it was impossible to ascertain the precise structure behind the patterns. It was not until 1950 that Linus Pauling, working with R. B. Corey and constructing models that could be tested by trial and error, discovered that the keratin molecule in hair, along with many other proteins, is arranged in the form of a helix. This was a single strand twisted much like an extensible telephone cord, in a shape that is now named the alpha-helix.

Apart from its occurrence in strands like hair, the alpha-helix is also found in the globular proteins, myoglobin and hemoglobin, but in this setting they are coiled up in a ball. To work with three-dimensional molecules such as these, one has to cut many parallel sections through the molecule, make x-ray photos of each section, and then make two-dimensional contour maps of the density distribution in each section. From these it is possible to reconstruct the three-dimensional molecular structure that, when examined under x-rays, produces density distributions similar to those observed. The number of calculations required is vast, however, and could not be attempted without the use of high-speed computers. If only a few sections are made through the molecule, this simplifies the calculations, but then a fuzzy picture, one with low resolution, results. To improve the resolution, a large number of sections must be made. When one realizes that myoglobin contains 2,500 atoms and hemoglobin some 10,000 atoms, the enormity of the task of identifying the positions of atoms or atomic groupings along the chains becomes apparent. Nonetheless John Kendrew and Max Perutz, working at Cambridge, perfected the technique to the point where it could yield definitive results with globular proteins. For this they were awarded the Nobel Prize in chemistry in 1962.

Using such methods at their laboratory in King's College, London, Maurice Wilkins and Rosalind Franklin had previously set to work to ascertain the structure of the DNA molecule. Still earlier attempts had been made on this project, but the first photographs were so diffuse as to be of little use. By 1953, however, Wilkins and Franklin were getting much-improved results, and hopes were being revived of solving the problem of the structure of DNA by x-ray diffraction. By this time, Francis Crick was talking of DNA in Kendrew's laboratory at Cambridge, where he had been joined by a young American, James Watson. The two, who already knew of the base-pairing rules discovered by Chargaff, were given access to Franklin's photographs. Very quickly, by constructing models in much the same way as Pauling had discovered the alpha-helix structure in protein molecules, they arrived at the conclusion that the DNA molecule had the structure of a double helix. This is pictured in Fig. 3.4 of Sec. 3.3 above.

How they did so is described somewhat dramatically by Kendrew. Shortly after his arrival at Cambridge, writes Kendrew, Watson

> began to talk to Francis Crick, who was already in our laboratory, about the importance of solving the structure of DNA. They looked at the new x-ray photographs, they wondered about Chargaff's base-pairing rules, they tried out all sorts of models, and the upshot was that in only a few weeks, after one or two false starts, they actually solved the whole thing! I would find it very hard to explain just how they did solve it—indeed, I think they would find it hard too. It is a good example of one of those intuitive jumps which happens in science from time to time. You may call it genius, you may call it inspiration, or what you will. One thing is clear, that the jump could not have been made earlier than 1953, because it absolutely depended upon a knowledge of the base-pairing rules and of the information contained in the improved x-ray photographs. But once these had become available it became possible to find the answer in a remarkably short time.[32]

The "false starts" to which Kendrew refers in this passage can be explained in terms of the situation at Cambridge and London in 1953. Pauling's discovery in 1951 of a helical structure in proteins had set the groups at both places thinking that DNA might be a helix as well. Franklin was the only researcher to reject the helix hypothesis at this

32. *The Thread of Life*, p. 61.

stage, and she was doing the best crystallographic work at the time, but Wilkins thought it might actually be several helices twisted together. Similarly, working with his group in the U.S., Pauling had produced two versions of his own model of DNA, which contained three twisted helices. In their first attempt, Watson and Crick, who had been studying Pauling's work on the chemical bond, likewise proposed a three-helix model. When they showed this to Wilkins and Franklin, the latter pointed out that it disagreed with her diffraction data and also had other defects. Watson then learned more about discerning helical structures from diffraction techniques and Crick worked on the pairing of the bases. Both had neglected the positions of the sugars in the chains, and Franklin made suggestions about that. After another abortive attempt, Watson built a model that incorporated two helices, paired bases, and the sugar structure recommended by Franklin. Crick's calculations quickly showed that this model was consistent with his data. Wilkins and Franklin produced calculations based on their diffraction data, and these confirmed the structure as well. Linus Pauling then flew over from the U.S., saw the defects in his model when compared to that of Watson and Crick, and added his assent to that of the rest. By consensus all three teams working on DNA thus agreed, early in 1953, that the problem of its structure had finally been solved.

In 1962 Watson, Crick, and Wilkins were awarded the Nobel Prize in Medicine for their work on DNA. (Rosalind Franklin had poor health, and she died in 1958; her death automatically precluded her being considered for the prize.) In the same year, Kendrew and Perutz, as already noted, received the Nobel Prize in chemistry for their work on hemoglobin, and Pauling, who earlier had received the Nobel Prize in chemistry for his study of the chemical bond, was given the Nobel Peace Prize for his opposition to atmospheric testing of nuclear weapons. Thus the stamp of approval of science's highest award system was put on all the parties involved in elucidating the structure of DNA, making it one of the best-certified discoveries in the recent history of science.

Watson and Crick made their initial announcement in the April 25, 1953, issue of *Nature* in an article entitled "A Structure for Deoxyribose Nucleic Acid." Toward the conclusion of the article the authors wrote:

> The previously published x-ray data on deoxyribose nucleic acid are insufficient for a rigorous test of our structure. So far as we can tell, it is roughly compatible with experimental data, but it must be regarded as unproved until it has been checked against more exact results. Some of these are given in the following communications. We were not aware of the details of the results presented there

when we devised our structure, which rests mainly though not entirely on published experimental data and stereochemical arguments.

It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material. . . .[33]

The "following communications" to which they referred were two. The first, by M. H. F. Wilkins, A. R. Stokes, and H. R. Wilson and entitled "Molecular Structure of Deoxypentose Nucleic Acids," described the authors' findings relating to the helical configuration of the polynucleotide chain and concluded that "in general there appears to be reasonable agreement between the experimental data and the kind of model described by Watson and Crick" in the preceding communication.[34] The other, by Rosalind Franklin and R. G. Gosling and entitled "Molecular Configuration in Sodium Thymonucleate," stated that their x-ray diagrams, while not offering direct proof, exhibit "in striking manner the features characteristic of helical structures." Other considerations, they continued, "make the existence of a helical structure highly probable." They went on to make additional comments, noting toward the end that their "general ideas are not inconsistent with the model proposed by Watson and Crick in the preceding communication."[35]

All of these articles appeared in the April 25, 1953, issue of *Nature*. Five weeks later, in the May 29, 1953, issue of *Nature*, Watson and Crick elaborated on the cryptic "It has not escaped our notice . . ." of the first paper. They did so in a second article, entitled "Genetical Implications of the Structure of Deoxyribonucleic Acid." In it they noted that the x-ray evidence presented by Franklin and Gosling in the earlier issue gave "qualitative support" to their structure and "is incompatible with all previously proposed structures." This, they observed, engendered in them "sufficient confidence in its general correctness to discuss its genetical implications."[36] They then went on to explain how the DNA double helix embodies within it the capacity for its own replication, thus anticipating the mechanism that later was developed more fully and has already been explained in Sec. 3.3 above.

The speed with which the Watson-Crick model was arrived at sug-

33. Cited from the Norton Critical Edition of James D. Watson, *The Double Helix: A Personal Account of the Discovery of the Structure of DNA*, ed. Gunther S. Stent, with text, commentary, reviews, and original papers, New York-London: W. W. Norton, 1980, p. 240.

34. Ibid., p. 251.

35. Ibid., pp. 253, 256.

36. Ibid., pp. 241–242.

gests a comparison with Galileo's achievement in seeing in his telescopic observations at Padua evidence for the existence of both mountains on the moon and satellites orbiting Jupiter. Both discoveries were made very quickly once the relevant data were available, and both involved the use, at least implicit, of the demonstrative regress. Accordingly, we present Watson and Crick's finding in the same format we have used earlier in this chapter to schematize those of Galileo and others:[37]

First progression: ***from effect to cause—the cause is materially suspected but not yet recognized formally as the cause.***

Effect	**Cause**
Various chemical and stereometric properties of the salt of deoxyribose nucleic acid (DNA)	suggest that its molecule has the structure of two helical chains each coiled around the same axis

Intermediate stage: the work of the intellect, testing to see if this is a cause convertible with the effect, eliminating other possibilities.

The model for nucleic acid proposed by Pauling and Corey, consisting of three intertwined chains, with the phosphates near the fiber axis and the bases on the outside, is unsatisfactory, for two reasons: (1) the material that gives the x-ray diagrams is the salt, not the free acid, and (2) some of the van der Waals distances appear to be too small.

Another three-chain model, suggested by R. D. B. Fraser and having the phosphates and the bases on the inside, linked together by hydrogen bonds, is ill-defined and not a candidate for consideration.

The correct model consists of two ribbons or phosphate-sugar chains that are held together by rods that represent pairs of bases. Both chains follow right-handed helices, but the sequences of the atoms run in opposite directions. The phosphates and sugar groups are on the outside of the helix while the bases are on the inside. The essential element of the structure is the manner in which the two chains are held together by hydrogen bonds between the bases. The bases are perpendicular to the fiber axis and joined together in pairs. The pairing arrangements are very specific, and only certain pairs of bases will fit into the structure. Any sequence of bases can do this, but a specific pairing demands a definite relationship beween the sequences of the two chains. If one knows the actual order of the bases on one chain, one can automatically write down the order on the other. The structure thus consists of two chains, each of which is the complement of the other.

37. The material contained in this summary has been extracted from the two papers of Watson and Crick that appeared in the April and May 1953 issues of *Nature* cited above, as well as a somewhat fuller report the authors gave in June 1953 at the Eighteenth Cold Spring Harbor Symposium. See ibid., pp. 257–274.

This model is verifiable by crystallographic analysis. Two distinct forms of DNA exist: one is a crystalline form, the other is less ordered and appears to be paracrystalline. The repeat distance along the fiber axis is 28Å for the first form and 34Å for the second, which has higher water content. Within limits, other dimensions of the structure can be specified in Angstrom units.

The model is also capable of explaining how the genetic material in the molecule is replicated. Previous discussions of self-replication have involved the concept of a template. This model is, in effect, a pair of templates, each of which is complementary to the other. It seems likely that the precise sequence of the bases is the code that carries the genetic information. Prior to duplication, the hydrogen bonds are broken, and the two chains unwind and separate. Each chain then acts as a template for the formation on itself of a new companion chain, so that eventually there are *two* pairs of chains where previously there was only one. Moreover, the sequence of the pairs of bases will have been duplicated exactly.

Suppositions: 1. The normal chemical supposition has been made, namely, that each chain consists of phosphate di-ester groups joining ß-D-deoxyribofuranose residues with 3´,5´ linkages, and so on.

2. The x-ray diffraction data currently available supports the structure here proposed. Its ultimate proof will come from further crystallographic analysis.

Second progression: ***from the cause, recognized formally as the cause, to its proper effect.***

Cause	Effect
The structure of deoxyribonucleic acid (DNA) as a double helix with complementary chains as described above	accounts for the chemical properties of the molecule and its stereometric properties in x-ray diffraction; it also provides a plausible mechanism for genetic replication.

Apart from the technical details set forth in the intermediate stage, the basic argument is quite simple. It goes in the first progression from effects that were generally known to a cause that might serve to explain them, and then, in the second progression, returns from that cause, now more fully explicated, to a detailed account of why the effects occur as they do. The pattern, on this reading, is not very different from Galileo's demonstrations based on his early findings with the telescope. One notable difference, however, is that Watson and Crick's discovery was accepted almost immediately by the scientific community. In this it was quite unusual, unlike Galileo's experience, and not only his, but those of the other investigators whose contributions have been sketched in this chapter.

10 Controversy and Resolution

Most of the conceptual studies presented in the previous chapter contained proofs that when formulated were regarded as demonstrations or as apodictic arguments, and yet not one, with the exception of the last, was immediately accepted by those to whom it was proposed. Is this an anomalous situation, or is it something that is to be expected in matters pertaining to science's epistemic dimension? Aristotle wrote the *Posterior Analytics* with the idea in mind that it might provide canons that would prove useful "in teaching and learning through discourse" (71a1), meaning by discourse (Gr. διανοητικός) the use of a reasoning process on the part of both the teacher and the taught. Presumably he was aware that proposing a demonstration to others is not a simple matter, that those who come upon a truth previously or generally unknown and wish to communicate it to others take on a difficult task. Invariably they must assume the role of teacher, and this brings with it the risk that those to whom they are proposing the demonstration might not wish to be taught. The situation, when transposed into the scientific community, by its very nature invites controversy. This is further exacerbated by the content of what is being proposed: a certain and necessary truth, one that cannot be other than it is. Truth is one thing, but an infallible and irrevisable truth seems to be something else entirely.[1] In cases such as this, a kind of reserve toward acceptance might normally be expected.

To focus the problem further we should note that Aristotle's reference to discourse cited above was made in the very first sentence of the *Pos-*

1. It was considerations such as this that surely gave Pope Urban VIII cause for concern, since taken in the context of Renaissance cosmology it would seem to limit God's omnipotence. For example, if a physical truth is not contingent but necessary, one might have difficulty seeing how God could have created a world different from

terior Analytics, where he introduces the theme of foreknowledge required for demonstration (Sec. 8.5). Here he is making the point that not *all* knowledge is acquired through discourse. The two types that are not so acquired are knowledge of facts and understanding (Gr. ξυνιέναι) of expressions. Both of these are essential for comprehending a proposed demonstration. Since knowledge of the facts must precede discourse, those to whom a demonstration is proposed must have belief in at least some facts, namely, those that occur in the initial statements on which the discourse will be based. They must also understand the terms and expressions in which these statements are couched. Such terms are based ultimately on sensations of individual objects, but sensations are not the same as concepts, and for understanding one must grasp concepts. As explained in Sec. 4.5, sensations alone are not sufficient to produce a concept, for abstraction is also necessary. Only through abstraction is the universal attained, the intelligible meaning that is the goal of the process of understanding.

These requirements are difficult to fulfill when one is dealing with facts provided directly in sense knowledge and with concepts based on ordinary experience. The requirement for factual status is more difficult to meet when one is dealing with metrical concepts, because of the problems involved with measurement and the instrumentation it requires (Sec. 7.1). Much of the controversy we shall see in subsequent sections is occasioned by problems of this sort. Even more difficulty is experienced when the discourse involves theoretical concepts (Sec. 7.2). The added complication arises from the hypothetical nature of such concepts and the logical construction involved in their formulation. The meanings attached to such concepts are rarely univocal, and for the most part they can be grasped only by analogy. Analogous concepts are compounded rather than simple; on this account they are confused and indistinct, as opposed to clear and distinct. Clear and distinct ideas appeal to mathematicians, and Descartes proposed them as the ideal for the philosopher, but unfortunately they are not pervasive in the discourse of modern science.

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the existing one (see Enrico Berti, "Implicazioni Filosofiche della Condanna di Galilei," *Giornale di Metafisica* 5 [1983], pp. 239–262). In Thomistic natural philosophy, however, this is not an insuperable difficulty. All demonstrations in that discipline are made on the supposition of an existing order of nature (supposition [1] in Sec. 8.4 above). If that order of nature is changed, as it could be by God's creative action, the demonstration is rendered invalid and a necessary truth is no longer involved.

A related consideration is one pointed out by Aristotle at the beginning of the *Physics*. This arises from the need in human knowing to proceed from what is more known and clearer in the order of sense and perception to what is more known and clearer in the order of intellect. But what is more known and clearer in sensation is the unanalyzed whole, a composite that, as Aristotle puts it, is mingled or confused (Gr. συγκε–χυμένα, 184a23) and has to be broken down into its components to be clearly understood. One "senses" a human being as a whole long before one is aware of the systems that make up the human body and its integral parts. The same could be said of the many animals and plants that fall under sense experience, to say nothing of minerals and heavenly bodies. As a consequence, most of the concepts that function in the early stages of natural science are "confused" in this sense, just the opposite of the clear and distinct concepts that function in the early stages of mathematical reasoning.

Paradoxically, however, this same situation is encountered in the process whereby one passes from dialectical argument employing *endoxa* to demonstrative arguments that employ causal reasoning. It is also found in the intermediate stage of the demonstrative regress, as analyzed by Zabarella and explained in an earlier chapter (Sec. 8.6). Reflection on this fact suggests a way out of the difficulties that have been enumerated and invariably give rise to controversy. The key is provided by the Aristotelian notions, little appreciated in the present day, of obscure truth and partial truth. The human intellect is the power that apprehends truth, but not all the truths it apprehends are the whole truth and nothing but the truth. As has been stated earlier, most of what most people know about the world in which they live must be classified, from an epistemological point of view, as opinion (Sec. 7.7). And yet most of what they know is true.

The history of science might be seen in much the same way as the history of individuals progressively learning more and more about their surroundings and thus coming to a clearer and more complete truth. The focus then would be on what is known prior to a scientific discovery, on the truth already possessed, rather than on the changes that result from the discovery. Unfortunately there is a tendency among philosophers to view scientific change pessimistically, as though it means a loss of truth rather than an addition to it. Scientific growth ought to be seen the other way around. Scientific controversy is not a sign that all truth claims are fallible, but rather that scientists are intent on rooting out error and misapprehension and so coming to a truth that is clearer and more complete than the truth they already possess.

10.1 The Demonstration Long Lost

The first analysis presented in the previous chapter, that of Theodoric of Freiberg's investigation of the rainbow, offers a convenient starting place from which to explore this approach to the history and philosophy of science. As far as is known, no controversy attended Theodoric's writing of *De iride*, and so the controversial aspect of his discovery need not be addressed. A Dominican friar, he was a master of theology and was present at three general chapters of his order, as recorded in *Acta* of the chapters that are still preserved. The first was held at Strassburg in 1293, the second at Toulouse in 1304, and the third at Piacenza in 1310. At Strassburg he was elected provincial of Germany, a post he held for three years, and at Piacenza he was appointed vicar provincial of Germany, to succeed a provincial who had resigned until another was elected. At Toulouse he told the master general of the order, Aymeric of Plaisance, of his work "on the causes and the mode of generation and appearance of the rainbow" and was told by Aymeric to commit it to writing.[2] Since the *De iride* is addressed to Aymeric as master general, a post from which he resigned in 1311, it seems certain that Theodoric wrote the treatise between 1304 and 1311. It is probable, however, that much of the research on which the treatise is based was completed by 1304.

Theodoric was an important philosopher and theologian in his own right, part of a circle that included Meister Eckhart and Berthold of Moosburg and had significant influence on the Rhineland mystics. Only four manuscripts of his work on the rainbow survive to the present, and the scribes who prepared them had difficulty drawing the figures, thirty-nine in all, that accompany the text. The manuscripts themselves were not looked at by modern scholars until G. B. Venturi rediscovered them in 1814. Before that their existence was known to Regiomontanus (1436–1476) and to Francesco Maurolyco (1494–1575), but only Trutfetter supplied any details of their teaching, as noted in the previous chapter (Sec. 9.5). If Descartes knew of Theodoric's work through Trutfetter, his desire to have this overlooked would have suppressed any criticism and thus any hint of controversy attending Theodoric's discoveries.

The interesting point is not the appropriation of Theodoric's work by a later tradition but rather the sense in which Theodoric's demonstration of various properties of the primary and secondary rainbow can be said to be apodictic. The problem latent here is that of partial truth, whether

2. *The Scientific Methodology of Theodoric of Freiberg*, p. 174, pp. 10–20.

or not Theodoric had uncovered a complete causal explanation of the rainbow in light of the later discoveries of Descartes and Newton. And if he had not, in what sense can his work be seen as measuring up to the ideal of demonstration as set out in the *Posterior Analytics*, which he had proposed to follow in his treatise?

To appreciate the difficulty one must understand additional matters that are treated in the *De iride* but were not discussed in the previous chapter. One of these is the number of colors in the rainbow, which, as has been seen, are listed by Theodoric as four: red, yellow, green, and blue. Now the Aristotelian teaching, found in previous explanations and dominant in Theodoric's day, was that there are really only three colors in the bow: red, green, and blue. Aristotle had admitted that a yellow band often appears between the red and the green, but he attributed it to the contrast between red and green, "for red in contrast to green appears light" (375a7), and so dismissed the yellow band as a lighter appearance and not a true color.

To refute this teaching, Theodoric launched into an extensive dialectical argument based on contraries to discover the principles of radiant color, that is, color as seen in the light rays that produce the rainbow.[3] He distinguished "radiant colors" (*colores radiales*) from those seen in opaque bodies, what he called "natural colors of absolute quality" (*colores naturales absolutae qualitatis*), and he used the principles Aristotle proposed for natural colors to determine analogous principles for radiant colors.[4] Aristotle had defined color as the extremity of the translucent within a bounded body. From this definition Averroes had advanced the idea that the principles of natural colors are basically two: luminosity (*luminositas*) and transparency (*diaphanitas*). From this Theodoric went on to argue that both of these allowed of degrees, "greater and lesser." So he associated greater and lesser luminosity with "the extremity of the translucent" and greater and lesser transparency with the "bounded body," and thus arrived at four principles for natural colors. For radiant colors, reasoning proportionately, Theodoric then proposed perspicuity (*perspicuum*) and boundedness (*terminatum*) as the basic principles, and to these he added "greater and lesser" as further differentiating principles. Based on more or less perspicuity, these principles

3. *Scientific Methodology*, pp. 188–205.

4. In his *Opticks* Newton referred to the colors Theodoric called natural as "permanent colours" and to those he called radiant as "colours made by light." But whereas Theodoric used natural colors to investigate the principles of radiant colors, Newton did just the opposite, using colors made by light to investigate the causes of permanent colors—*Opticks*, ed. cited, pp. 179–185.

yield two clear colors, red and yellow, and two obscure colors, green and blue. With the clear colors, when based on boundedness and its opposite, unboundedness, reception in boundedness results in red whereas reception in unboundedness results in yellow; with the obscure colors, reception in unboundedness results in green whereas reception in boundedness results in blue. Then, examining the paths of light rays through raindrops or prisms, Theodoric proceeded to identify the conditions under which these principles are verified and the various radiant colors generated. In the case of the primary rainbow, he used this reasoning to justify the order in which the radiant colors are projected to the ground and then how they are seen by the observer (predicates [8] and [9] in the polysyllogism given in Sec. 9.1). A similar application of the principles to the case of the secondary rainbow yielded for him the reverse ordering of the four colors as they are projected and seen, when the situation is such that both rainbows appear.

Now it is important to note that Theodoric does not identify his investigation of radiant color as demonstrative, but sees it only as dialectical. This follows from the fact that he does not pretend to have discovered the causes of the colors, but only principles that may be sufficient to account for them. To identify these principles he uses *topoi* of the type that are classified by Boethius as intrinsic topics. As already noted (Sec. 7.8), these are divided into three groups: topics in the first group pertain to the thing itself, such as definition; those in the second group pertain to matters conjoined with the thing, such as causes and antecedents; and those in the third group pertain to matters disjoined from it. It is in this third group that one finds "greaters and lessers" and "opposites," a subspecies of which is "contraries." Arguments from contraries are topical arguments, and they are precisely the type of argument Aristotle used to identify the four elements (from the contraries "hot-cold" and "moist-dry"), as Theodoric himself acknowledges at the end of this portion of his investigation.[5]

As opposed to the problem of radiant colors, Theodoric proposes his explanation of the geometrical properties of the primary and secondary rainbows as demonstrative, as unveiling the causes in nature that make each type of rainbow be what it is. Crucial to his discovery is his having identified radiation through the spherical raindrop as the basic cause for

5. *Scientific Methodology*, p. 194. Theodoric also wrote treatises on the elements, *De elementis*, and on the nature of contraries, *De natura contrariorum*, in which he analyzed in detail the role of contraries in the discovery of principles and elements; see ibid., pp. 80–130.

each and the two opposed modes of radiation as the differentiating factor between them. And it is noteworthy that Descartes uses his adoption of precisely these causes to illustrate his method of arriving at what he claims to be "knowledge not possessed at all by those whose writings are available to us."[6] Newton furnishes the same diagram as does Descartes, and credits Antonius de Dominis and Descartes with its discovery, while pointing out that the two "understood not the true origin of colors."[7] As for Theodoric's discussion of luminosity and boundedness, this may now seem hopelessly archaic, but one should observe that Newton's first theorem in the second part of Book I of his *Opticks* reads that "Colours produced in refraction or reflection are not caused by modifications of the light due to bounding conditions of light or shadow,"[8] which shows that the peripatetic view was still being considered a live option in his day.

Related to the question whether Theodoric's demonstration had attained a partial truth, despite Descartes' more precise measurement of the angles at which the various colors are produced and Newton's demonstration of the cause of the colors, one might inquire whether Aristotle had similarly demonstrated a partial truth about the rainbow in his *Meteorology*. There he identified three fundamental elements involved in its production, namely, a light source such as the sun, a rain cloud from which rays are reflected, and the eye of an observer who sees it. He then invoked geometrical demonstrations to show that the rainbow is always some portion of a circle, since the reflection of light to the eye of the observer "takes place in the same way from every point" in the cloud (373a3). This Aristotle explains in a way that is equivalent to Theodoric's middle term [11] and his predicate [12] in the polysyllogism given in Sec. 9.1. His main defect here is that he shows no knowledge of Theodoric's middle term [2], which explains how both reflection and refraction work in the production of the bow. For Aristotle only reflection is involved, reflection from a cloud whose surface he thought of as constituted of tiny little mirrors. And, of course, the mechanism whereby light is sent back to the eye of the observer need not be known to prove that the arc of the rainbow is circular, as long as the angle of incidence and reflection from the cloud remains the same from every point. One could say, therefore, that Aristotle had demonstrated a partial truth about the rainbow, less complete than Theodoric's proof, but a truth nonetheless. But perhaps it would be better to say that he had demonstrated an

6. *Meteorology*, Eighth Discourse, ed. cit., p. 332.

7. *Opticks*, ed. cit., p. 169

8. Ibid., pp. lxxxiv, 113.

"obscure truth" about the rainbow, because he did not understand the bow's circularity as clearly as did Theodoric. Aristotle's understanding of the term "reflection" was obscure, because he implicitly included under that term what was later to be known as "refraction." (The same could not be said of Roger Bacon, who knew the difference between reflection and refraction and despite this maintained that only reflection was involved in the generation of the rainbow. On this account, Bacon failed to understand the rainbow, even though his optical knowledge was much advanced over Aristotle's.)

From the foregoing analysis, scientific knowledge of the rainbow could be said to become clearer and more distinct with Theodoric's discoveries, even though it was still partial and incomplete. It would become yet more distinct and certainly more complete with the discoveries of Descartes and Newton. Indeed, one might wonder, with respect to the primary and secondary bows, whether there was anything more to discover about these atmospheric phenomena, whether, after over twenty centuries of search, the book had finally been closed on this fascinating subject. But, however one answers that question, it seems that the notions of obscure truth and partial truth remain quite relevant to the discussion of truth and certitude in modern science.

10.2 The Face of the Moon

Newton's account of the origin of colors did in fact prove to be controversial, and this will be discussed below in Sec. 10.5. But following the order of the demonstrations proposed in the previous chapter, we turn now to Galileo's discoveries with the telescope. These were truly momentous, and they appear so striking in the present day that one wonders how they could have provoked controversy when they were first proposed. They take on special interest for this study in that they involve the use of an instrument, and so raise difficulties similar to those now associated with metrical concepts; they also introduce entities that in Galileo's time were previously unobservable, and so raise difficulties similar to those now associated with theoretical concepts.

Galileo's study of the surface of the moon, as explained above in Sec. 9.2, had led him to state that "sane reasoning cannot conclude otherwise" than that there are mountains and valleys on the moon similar to those on the earth. Yet there was an observational difficulty that might call into question the intermediate stage of his demonstrative regress as formulated in Sec. 9.2. This may be stated as follows. The periphery of the moon is never seen as uneven, rough, and sinuous, the way the terminator appears through the telescope, but is exactly round and circular. Therefore there are no mountains on the moon, for if there were, its edges seen through the telescope would be ragged like a sawtooth. The difficulty either occurred to Galileo or it was presented to him some time between January and March of 1610, for he raises it in the *Sidereus nuncius* and proposes two answers to it. The first is that chains of mountains close together, such as those that cover the moon's surface, create the impression of a flat and regular surface when seen from a distance, and this explains the circular appearance of its edge. The second is an *ad hoc* hypothesis: perhaps an "orb of denser substance than the rest of the ether" surrounds the lunar body and inhibits our vision so that we do not see the actual shape of the body; thus we perceive its edge as circular even though it really is not (GG3.1:69–71).

The second reply was unfortunate, and Galileo later withdrew it. It caused difficulty for Christopher Clavius, who apparently seized on it to raise the possibility that the moon's surface is not uneven but that its body has denser and rarer parts that reflect light in ways that merely suggest a mountainous terrain (GG11:93). Three other Jesuit astronomers at the Collegio Romano were less concerned about it, apparently satisfied with Galileo's first reply to the difficulty. They expressed the opinion that the moon's surface was indeed uneven, but were "not certain enough about this to confirm it indubitably" (GG11:93). Within a year of the appearance of the *Sidereus nuncius*, all four had been requested by Cardinal Bellarmine, himself a Jesuit, to evaluate Galileo's discoveries with a telescope that had recently been constructed at the Collegio. Obviously the resolving power of this telescope, compared to Galileo's, was the key to their response. Bellarmine wished to know if "these new discoveries are well founded, or if they are apparent and not real" (GG11:88).[9] Thus his interests paralleled our own, since "well founded" could mean "demonstrated" in his day, and to inquire about the "real" vs. the "apparent" reveals a distinct epistemic concern on his part.

Apart from Clavius's doubt about the mountains on the moon, all four astronomers were unanimous in their replies to Bellarmine's queries, which were five in number. These may be summarized as follows. (1)

9. Here and elsewhere we use the translation of Albert Van Helden in his Galileo Galilei, *Sidereus nuncius, or the Sidereal Messenger*, Chicago-London: University of Chicago Press, 1989, pp. 110–112. Van Helden's Introduction and Conclusion to this work supply the main information required to understand how Galileo's discoveries were received by the astronomers of his day. Additional details will be found in the notes of Isabelle Pantin to her new French translation of Galileo Galilei, *Sidereus nuncus, Le messager céleste*, Paris: Les Belles Lettres, 1992, pp. 49–94.

With regard to the existence of small stars invisible to the naked eye in the Milky Way and "nebulosities," this they confirmed as true, though not so as to exclude completely the existence of "continuous denser parts" in these portions of the heavens. (2) As to Saturn's not being a simple star but three stars joined together, their reply was that Saturn appeared to have an oval, not a circular, shape, but that a distinction into three stars was not observed. (3) On the matter of Venus's waxing and waning like the moon, this they affirmed as "very true." (4) The moon's having a rough and uneven surface was assented to by three and questioned by one (Clavius), as mentioned above. (5) Whether four "movable stars" go about the planet Jupiter, this too they affirmed unconditionally; they found the stars' motions to be "very swift," different from those of fixed stars, continually changing their distances from each other and from Jupiter. Thus, on all the existential or ontological questions, the replies were unambiguously affirmative, thereby certifying the telescope for the first time as "a genuine scientific instrument."[10]

This was a surprising confirmation, since it came from the seat of orthodoxy in the Catholic Church within a year of the publication of Galileo's findings. Galileo's claims in the *Sidereus nuncius* were surely controversial, and for a variety of reasons. First, the spy-glass, as it was then called, presented a serious epistemological problem: how was one to know that the eye was not deceived by it and that the appearances perceived were not an optical illusion? Second, the results were proposed by a mathematical astronomer, and at the time they were notorious for the imaginary devices they constructed to explain the phenomena of the heavens. Third, apart from the illusion aspect, was it not possible that what Galileo had seen could be explained by earthly exhalations or other terrestrial cause, without assigning a cause in the celestial regions? And finally, if Galileo's conclusions were accepted on face value, the reigning cosmological system of Ptolemy, which then fitted so well with accepted philosophical and theological teachings, would be overthrown, and how could one replace it? In particular, how could the perfection and ideal circularity of the heavenly bodies be maintained, if the face of the moon is scarred with mountains and valleys like the surface of the earth?

The last difficulty caused so much difficulty for conservative Aristotelian philosophers that some rejected Galileo's claims out of hand, refusing even to look through his telescope to see for themselves. The more progressive and enterprising types sought to acquire telescopes so as to test the results independently of Galileo's instrument, but well-

10. Van Helden, Conclusion, p. 112; see previous note.

ground lenses proved almost impossible to acquire. Of the sixty telescopes Galileo himself had made by March of 1610, by his own admission only a few were able to detect the moons of Jupiter (GG10:343). To make matters worse, by May Jupiter was too close to the sun to be observed, and it was not until July that it could be seen in the morning sky. Not until late September did Galileo receive word from his friend Antonio Santini in Venice that the latter had seen all four satellites. Earlier in the month Kepler was able to observe them at Prague, using a telescope Galileo had sent to the Elector of Cologne. Unknown to Galileo, Thomas Harriot detected Jupiter's moons in England in late October, and two French observers at Aix-en-Provence did the same in late November.

In July of 1610 Saturn also became visible, and Galileo was then able to observe its peculiar shape, on which the Jesuit astronomers would later comment. Venus became visible in the evening sky in October, and Galileo began studying it more seriously. By the end of December he had obtained the information he would send to Castelli and which has been summarized in the previous chapter (Sec. 9.2). On December 17th Clavius had written that he had seen innumerable stars invisible with the naked eye, that he had satisfied himself that the bodies moving around Jupiter were its moons, and that he had observed Saturn to have an oval shape (GG10:484–486). By the spring of 1611 additional confirmations were at hand, including those at the Clavius's colleagues in Rome. Among astronomers there could no longer be any doubt of the validity of the information provided by the telescope.

As that instrument was improved in magnification and resolving power, all of the difficulties latent in Galileo's demonstrations were eventually resolved. The particular question of why the edge of the moon does not appear like the outline of a toothed wheel was not answered until 1664. By that time Giovanni Domenico Cassini had a telescope good enough to show the remaining small irregularities in the limb of the moon. Thus he vindicated Galileo's explanation in the *Sidereus nuncius*, namely, that the valleys are filled in by the peaks of mountains in front of and behind them, and so the imperfections in the circular outline are largely obliterated. Earlier, in 1656, Christian Huygens solved the problem of Saturn's odd shape, noting that the "handles" Galileo had seen on that planet were actually rings. In the same year Huygens also discovered Titan, Saturn's largest satellite.

Thus the demonstrative character of Galileo's claims were certified by those who had access to the facts and acquired sufficient conceptual knowledge to understand them. There remains, however, an unsuspected problem relating to Galileo's style in communicating his results. This was not a problem in his day, but it has been made into one in our own. In a recent translation of the *Sidereus nuncius* into French, Fernand Hallyn portrays that work from the viewpoint of its being a rhetorical treatise rather than a demonstrative exposition of Galileo's findings.[11] In light of more extensive work by Jean Dietz Moss, there can be no doubt that Galileo employed both rhetoric and dialectic to good effect in making his arguments intelligible to his readers. So good was he at that effort that Moss has argued for his being not only the father of the scientific revolution but also of a second revolution, a rhetorical revolution, in the methods he used to gain assent to the Copernican system.[12] But whereas Hallyn inclines toward a literary view of Galileo's contribution and so slights its epistemic value, Moss sees Galileo's use of rhetoric and dialectic to be compatible with his also employing demonstrative reasoning in his discourse. In her view the two weaker forms of argument prepare for and augment the force of Galileo's proofs, which remain strictly scientific in the Aristotelian sense. Her analysis accords well with the relationships between science, dialectic, and rhetoric taught in the logic course Galileo appropriated,[13] whereas Hallyn's reflects the "social constructivist" view of science that has recently been advanced and is explained in a previous chapter (Sec. 7.9).

To return to the probable and fallible character of modern science, is it absolutely certain in the present day that there are mountains on the moon, that Jupiter has satellites, and that Venus orbits the sun rather than the earth? If the answer is affirmative, as it must be, at what point in time did this become scientific knowledge in the strict sense? According to Van Helden, that status had been substantially achieved within a year of the publication of the *Sidereus nuncius*, notwithstanding the doubting Thomas's who voiced objections or continued to withhold assent. Presumably, with the improvement of telescopes and the increase in the number of observers who certified Galileo's findings, the situation had improved dramatically within about fifty years of the publication. Or were there still lingering doubts even then because an instrument such as the telescope had to be used to establish these facts? With regard to

11. Galileo Galilei, *Le Messager des étoiles*, trans. Fernand Hallyn, Paris: Éditions du Seuil, 1992.

12. In her *Novelties in the Heavens: Rhetoric and Science in the Copernican Controversy*, Chicago: University of Chicago Press, 1993, pp. vii-ix.

13. On the way science, dialectic, and rhetoric were seen to be related in Galileo's day, see chap. 3 of *Galileo's Logic of Discovery and Proof*. A fuller exposition will be found in Moss, *Novelties*, pp. 1–23.

the mountains on the moon, did it make a difference when astronauts finally landed on the moon and were able to see the mountains with their own eyes? It would seem that there are degrees of certitude, and "absolutely certain" might mean different things to different people. Just as in the last section we spoke of partial truth in conjunction with the details of the rainbow, perhaps we should speak of obscure truth in the present context. If so, increases in the resolving power of the telescope led to an increasingly clear perception of these astronomical phenomena. In the case of the mountains, seeing them with unaided vision removed every vestige of doubt, for the astronauts and for others through pictures sent by them to earth.

But was Galileo's, or Cassini's, claim any less true for their having less clarity, say, than Neil Armstrong in their perceptions of the unevenness in the moon's surface? It would seem that Galileo had attained the truth right off, not so much for the acuteness of his vision as for the quickness of his mind (Gr. ἀγχίνοια, Lat. *solertia*). Aristotle attributed this quality to those who hit upon a middle term without a moment's hesitation, who grasp a proof right away. The example he gives is that of the person who notes that the moon always has its bright side facing the sun and immediately grasps the cause, namely, that it is illumined by the sun (89a10–12).[14] One could say that others, for a variety of reasons, proved slower than Galileo, but eventually they caught up and were able to certify his discoveries. That took time, and predictably the first to do so were the experts, those who already had *endoxa* in matters astronomical. They gave social certification, one might say, to the proofs first seen by Galileo, and that has since become a requirement for any demonstration to be accepted within a scientific community. But social certification is not social construction. The demonstrations were there; it simply took time for others to grasp the middle terms and see them for what they were.

14. Ernan McMullin is critical of Aristotle here, holding that "a fairly elaborate theory of light" and "geometrical analysis" would be necessary for "absolute assurance" that the sun illumines the moon: see his "The Conception of Science in Galileo's Work," *New Perspectives on Galileo*, ed. R. E. Butts and J. C. Pitt, Dordrecht-Boston: D. Reidel Publishing Co., 1978, p. 215. His tendency, like that of many philosophers of science, is to move immediately to the level of theory, thus bypassing the possibility of anything self-revelatory at the levels of both sense and intellect. For a discussion of McMullin's views, see *Galileo's Logic of Discovery and Proof*, pp. 27–28, 234–236.

10.3 The Earth's Motion

Controversy surrounded Galileo's first discoveries with the telescope, but this was as nothing compared to his subsequent claims with regard to the earth's motion. As noted at the end of Sec. 9.2, shortly after the publication of the *Sidereus nuncius*, and particularly when accolades for the discoveries recounted in it began coming from all over Europe, Galileo got seriously interested in advancing the cause of the Copernican system. This goal he pursued for almost a quarter of a century, before being brought to almost a complete halt by his trial and condemnation in 1633 at the hands of the Roman Inquisition. But even after that, and possibly because of it, he continued developing his new science of motion, realizing that only this would provide the basis for future claims in favor of heliocentrism. Working away under house arrest at Arcetri, and using his manuscripts and records from his work at Padua before he made his observations with the telescope, he was able to complete the *Two New Sciences* and get it published by 1638. He had only four more years to live, and thus he did not see his study of falling motion gain complete acceptance in his lifetime. But he nonetheless laid a strong foundation on which Newton could erect his *Principia*, and he thus prepared the way for later proofs of the earth's motion.

The Law of Free Fall. The demonstrations Galileo would base on his definition of naturally accelerated motion, whose discovery has been sketched in Sec. 9.3, gained rather complete acceptance shortly after the publication of the *Two New Sciences*. Father Marin Mersenne made Galileo's ideas known in France and himself performed experiments directed at improving the preliminary results Galileo had reported in his *Dialogue Concerning the Two Chief World Systems* of 1632.[15] Mersenne was interested in removing the discrepancy he had uncovered between the times that pendulums of different lengths would take to reach the bottom of their swings over arcs of ninety degrees to the times that bodies would take to traverse the same vertical distances in free fall. In effect Mersenne was measuring *g*, the acceleration due to gravity. Galileo had not calculated a figure for this, but implicit in the measurements he describes in the *Dialogue* was a value close to half that now accepted for it. In his *Harmonie Universelle* of 1636, Mersenne reported experiments

15. For a summary of Mersenne's results, see Alexandre Koyré, *Metaphysics and Measurement: Essays in the Scientific Revolution*, Cambridge, Mass.: Harvard University Press, 1968, pp. 97–102.

that improved on Galileo's figures and brought them much closer to the modern value.

The most thoroughgoing confirmation of Galileo's law of free fall, however, was again to be provided by the Jesuits, this time not in Rome but in Bologna. There Giambattista Riccioli and his colleagues at the *Studium* in that city, unaware of Mersenne's investigations, likewise experimented with pendulums and falling bodies. At Parma, Riccioli had been a student of Giuseppe Biancani, one of the first Jesuits to comment favorably on Galileo's work, and himself a disciple of Christopher Clavius. In his *Almagestum novum* of 1651 Riccioli writes that he first started experiments on motion with two other Jesuits in 1629, and then with yet another in 1634; these led him to suspect that, in equal intervals of time, falling bodies traverse distances proportional to the odd numbers beginning with unity. He then obtained permission to read Galileo, whose works had been put on the Index of Prohibited Books as a consequence of the trial of 1633. Riccioli's more extensive studies at Bologna began after the publication of the *Two New Sciences*, in 1640, when he designed pendulums that could be used to measure small intervals of time and thus test Galileo's laws of free fall.[16] His co-experimenter in this project was Francesco Maria Grimaldi, the Jesuit who later achieved fame for his discoveries in optics.

With the aid of Grimaldi and others, Riccioli dropped spheres of equal size but different weights from the top of the Torre dei Asinelli initially to verify that heavy bodies fall quicker than light ones, though with only slight differences depending on the weights and dimensions of the balls. They then set about ascertaining whether the speed of fall is proportional to the time of fall or to the distance traversed and whether it is uniformly accelerated (*uniformiter difformis*).[17] To do so they manufactured a number of balls made of chalk, of identical dimensions and weight, and dropped them from different stories of the Torre dei Asinelli. Using the direct measurements they thus obtained, they then used an inverse procedure, dropping balls from other towers and churches in Bologna whose heights they could ascertain and corresponding times of fall they could calculate. Their results in all cases

16. The details of these experiments are likewise given in Koyré, *Metaphysics and Measurement*, pp. 102–108.

17. That is, uniformly accelerated with respect to time. It was common teaching among the Jesuits that falling motion was accelerated in this way. See my "The Early Jesuits and the Heritage of Domingo de Soto," *History and Technology* 4 (1987), pp. 301–320; also my "The Enigma of Domingo de Soto: *Uniformiter difformis* and Falling Bodies in Late Medieval Physics," *Isis* 59 (1968), pp. 384–401.

were completely congruent with Galileo's findings. Koyré observes that they compared very favorably to "the rough approximations of Galileo himself and even to those of Mersenne, . . . certainly the best ones that could be obtained by direct observation and measurement."[18] Only with the use of Christian Huygen's mechanical clock would better confirmation of Galileo's laws be obtained, and that would not come until 1659.

Does the Earth Move? But confirmation of the new science of local motion did not of itself constitute proof of the earth's motion. When Galileo had begun to campaign actively for acceptance of the Copernican system, and the Carmelite Paolo Foscarini had attempted to show how this system could be reconciled with the Bible, Cardinal Bellarmine had written to deter them both. That was in 1615. He advised them at that time to refrain from teaching that the sun is at rest in the center of the universe and that the earth moves around the sun until they could offer a true demonstration that such is actually the case. In his letter Bellarmine had ruled out the type of demonstration then being used by mathematical astronomers, that referred to as demonstration *ex suppositione*. This began by "supposing" or postulating that the sun is at rest and the earth in motion and then deducing all the appearances that could be expected to follow from this arrangement. In effect what Bellarmine was requesting was an experimental proof that would be independent of the theorizing implicit in hypothetico-deductive reasoning. Galileo himself attempted this type of proof in the argument from the tides, which he first proposed in his *Discourse on the Tides* of 1616 and then later in the *Dialogue Concerning the Two Chief World Systems* of 1632. In the latter work he also touched on two arguments, among others, that were relevant to the earth's motion, namely, the tower argument and the east-west gunshot argument. But both of these he dismissed as yielding the same result whether the earth is in motion or at rest. And the tidal argument, as is generally agreed, was defective and was not accepted by astronomers of his day or of our own.[19] Thus the demonstration Bellarmine had expected might be forthcoming did not appear, despite the progress Galileo had made with his new science of motion.

That the earth moves with a twofold motion, one of daily rotation on its axis and the other of annual revolution around the sun, was certainly a subject for controversy in the first part of the seventeenth century.

18. Ibid., p. 108.

19. For the two formulations that were actually proposed by Galileo and a brief discussion of them, see *Galileo's Logic of Discovery and Proof*, pp. 212–216 and 226–231.

Apart from the Church's condemnation of Copernican teaching on the grounds that it was opposed to the literal sense of the Scriptures, there was no way the earth's rapid rotation could then be detected in sense experience, nor were astronomical observations sufficiently refined to reveal the parallax that would be expected from the earth's motion around the sun. Not until Newton's *Principia* appeared in 1687 was there even sound theoretical ground for giving assent to the earth's motion. In Book III of that work, with Hypothesis I, Propositions XI and XII, and the Corollary to the latter, Newton clearly intimates that the earth moves along with the other planets. But to appreciate his argument one must accept the Definitions and Laws of Motion that precede Book I,[20] as well as the laws of planetary motion he develops in that book. Despite the axiomatic structure of the *Principia* as it appears in later editions, the demonstrations it contains are made *ex suppositione*, being based on principles arrived at by idealization and abstraction from actual physical situations. Thus, even by the early eighteenth century, Bellarmine's demand for a direct demonstration had not been met.

It is often said that the first experimental or *a posteriori* demonstrations of the earth's motion were not available until the nineteenth century. Definitive proof of the earth's revolution around the sun came in 1838 when Friedrich Bessel measured the parallax of star 61 Cygni, and similar proof of the earth's rotation on its axis came in 1851 when Léon Foucault performed his experiments with the pendulum.[21] It has recently been disclosed, however, that in 1820—even prior to these discoveries—the Church removed its prohibition against Copernican teaching, on the basis of earlier demonstrations of the earth's motion.[22] The occasion was the request of Giuseppe Settele, astronomy professor

20. Note that the three Laws of Motion were presented in the 1687 edition of the *Principia* not as laws or axioms but simply as hypotheses.

21. An earlier astronomical proof of the earth's motion that seems not to have come to the notice of the Roman authorities was the aberration of starlight, that is, a shift of as much as 20 seconds of arc in a star's position that is the combined effect of the velocity of light from the star and the orbital motion of the earth. The phenomenon was first measured by the English astronomer James Bradley in1728 and published in the *Philosophical Transactions of the Royal Society* in 1729. An Italian translation of the volume of the *Transactions* in which it was reported was available in Italy as early as 1734. Perhaps the fact that this effect is variable, generally very small, and at the time was detectable only by special instruments caused it to pass unnoticed as a directly measurable evidence of the earth's motion.

22. For details see Walter Brandmüller and Johannes Greipl, eds., *Copernico, Galilei e la Chiesa: Fine della controversia (1820), gli atti del Sant'Uffizio*, Florence: Leo S. Olschki Editore, 1992.

at the Sapienza (now the University of Rome), for permission to print the second volume of his *Elementa di Ottica e di Astronomia*, which taught, on the basis of new evidence, that the earth moves. Permission was denied by the Master of the Sacred Palace, Filippo Anfossi, who had jurisdiction in this matter, on the basis of the 1616 Decree against Copernicanism. Earlier, Settele had asked his colleague at the Sapienza, Benedetto Olivieri—who was professor of Old Testament there but also happened to be Commissary of the Holy Office, the branch of the papacy that had condemned Galileo—whether he could openly teach the earth's motion without running into difficulty with the Church. Olivieri, aware of changing interpretations of Scripture and the new astronomical evidence, had replied in the affirmative. A controversy thereupon ensued between Anfossi and Olivieri, both of whom were Dominicans. Olivieri, the more knowledgeable of the two, was able to convince Pope Pius VII and the cardinals of the Holy Office of the correctness of his views. The *imprimatur* was granted late in 1820, and the second volume of Settele's *Astronomia* came off the press on January 10, 1821.

The new scientific proofs mentioned by Olivieri in presenting his case to the pope are found in the works of two Italian astronomers, Giovanni Battista Guglielmini and Giuseppe Calandrelli. The first was professor of mathematics at the University of Bologna and the second was director of the observatory in Rome at the Collegio Romano. Olivieri pointed out that, in experiments performed at Bologna between 1789 and 1792, Guglielmini offered the first physical proof of the earth's rotation. Similarly, Calandrelli had measured the parallax of star Alpha in constellation Lyra and so presented what Olivieri identified as *una dimostrazione sensibile* of the earth's annual motion. This he had done in a work published in 1806 as *Osservazioni e riflessioni sulla parallasse annua dell'alfa della Lira*, dedicated to Pope Pius VII.[23]

For purposes here, Guglielmini's demonstration is the more interesting, since it involved the Torre dei Asinelli at Bologna, the same tower Riccioli had used for his experiments.[24] Actually Guglielmini took inspiration from a passage in Galileo's *Dialogo* where, on the Second Day, he is discussing the fall of an object from the orb of the moon to the

23. It is perhaps noteworthy that there is an entry on Giuseppe Calandrelli in the *Dictionary of Scientific Biography* (vol. 3, pp. 13–14) where this work is actually cited, but apparently its author, Giorgio Abetti, saw no special significance in the early date of Calandrelli's measurement.

24. For details, see Giorgio Tabarroni, "Giovanni Battista Guglielmini e la prima verifica sperimentale della rotazione terrestre (1790)," *Angelicum* 60 (1983), pp. 462–486.

earth's surface (GG7:259–260). Rather than falling to a point directly beneath the point from which it is released, the object should "run ahead of the whirling of the earth" and land at a point farther to the east. This should come about because, at the time of its release, the object would have a greater horizontal component in its motion the more distant it would be from the earth. The effect would not be noticed with objects dropped from a ship's mast or from a low tower, but it might be noticeable with those dropped from a high tower such as the Torre dei Asinelli. Isaac Newton was aware of this possible test, and so was Pierre Simon de Laplace, who suggested it to Joseph Jerome Lalande, director of the Paris observatory, who unfortunately never performed it. Thus it was left to Guglielmini to do so. He made a number of tests from the Torre at a height of 78.3 meters, and measured, on an average, a deviation of 19 mm. to the east and 12 mm. to the south. Concerned about atmospheric disturbances at the Torre, he also measured drops from a height of 29 meters from a spiral staircase inside the astronomical observatory of the Instituto delle Scienze at Bologna, and found a deviation there of 4 mm. to the east. Guglielmini was in communication with a German astronomer, Johann Friedrich Benzenburg, who dropped objects from the campanile of a church in Hamburg in 1802, at a height of 76.3 meters, and again from within a mine shaft at Schlebusch in 1804, at a depth of 85.1 meters, and obtained comparable results. Rough confirmation was also obtained by Ferdinand Reich, who performed tests in a mine shaft at Freiberg in Saxony, at a depth of 158.5 meters, in 1831. It turned out that longer falls were not necessarily more accurate indicators, because perturbing factors, both in the open air and within mine shafts, introduced effects much greater than that being measured. Definitive tests were finally made in the U.S. by Edwin Herbert Hall in 1902, working at Harvard under very controlled conditions, at a latitude close to that of Bologna. With a drop of 23 meters, Hall measured a deviation of 1.50 ± 0.05 mm. to the east (against a predicted value of 1.8 mm.) and of 0.05 ±0.04 mm. to the south.

When one considers the problems encountered in demonstrations such as Guglielmini's, one can appreciate the enormous difficulty of obtaining a consensus on such a fundamental matter as the earth's motion. Yet, in the present day, apart from dissenters such as might belong to the Flat Earth Society, scientists are agreed that the earth really moves, and that its motion can be demonstrated scientifically.[25] Again, in response

25. Some philosophers, on the other hand, might maintain that it is still logically possible to maintain that the earth is at rest in the center of the universe. Thomas

to the social constructionists, Guglielmini did not construct that motion, and even less did the Church authorities who acted in 1820 to remove the long-standing condemnation of Galileo, whose precise task was one of guarding against such construction. Galileo had suspected the truth about the earth's motion, and both Calandrelli and Guglielmini had attained approximate truths about it, which were to be made successively more accurate by Bessel, Foucault, Hall, and a host of other investigators down to the present day. And undoubtedly there are still additional truths to be learned about the earth's motion, whose acquisition will refine yet further the knowledge that has already been attained.

10.4 What Moves the Blood?

Although, as detailed above in Sec. 9.4, William Harvey offered a classical demonstration of the blood's motion in the Aristotelian mode, he did not gain assent from the Galenists of his day, and his teachings were opposed by two philosophers still heralded as key methodologists of the new science, Francis Bacon and René Descartes. Bacon had died two years before the publication of *On the Motion of the Heart and Blood*, but considering the fact that Harvey was his personal physician, it seems unlikely that he was unaware of Harvey's lectures at the Royal College of Physicians in 1616. Yet, when he published his *Novum Organum* in 1620, Bacon gave an account of the heart's motion that can only be called ludicrous in light of Harvey's researches. Descartes, on the other hand, had read Harvey's treatise, and indeed appropriated portions of it for his own use, but, brilliant of intellect though he was, he failed to grasp the demonstration it contained. The reception among lesser-known thinkers was no better, with the result that Harvey's great discovery was greeted with almost universal skepticism among his contemporaries. One such contemporary, the French physician Jean Riolan, criticized Harvey's exposition in his *Encheiridium anatomicum et pathologicum*, published at Leiden in 1648, and succeeded in eliciting two replies from Harvey. Since, in the second of these, Harvey took up Descartes' teaching also, we begin our discussion with Bacon's views, then consider Riolan's, and conclude with those of Descartes.

Bacon's discussion of the heart and pulse is found in the second book of the *Novum Organum*, where, after listing his inductive tables of pres-

Kuhn maintained that position in private correspondence to the author dated May 12, 1981, following the latter's request for clarification of a remark Kuhn had made in a letter to the editor of the *New York Times* dated April 30, 1981.

ence, absence, and degrees, he appended his twenty-seven "prerogative instances," which he thought to be of special value for eliminating accidental correlations and finding those that are essential. The twenty-fourth of these are what he calls "instances of predominance," wherein he exhibits the principal kinds of motions or active powers as an aid in clarifying their comparative strength. Bacon lists nineteen types of motion in all, the eighteenth of which is the motion of trepidation. He recognizes that this term has been used by medieval astronomers, but he is not employing it in their sense. Rather, he categorizes it as a motion of, as it were, "eternal captivity," when bodies, being placed neither altogether according to their nature nor in a way discordant with it, constantly tremble. They are restless, he observes, not contented with their position and yet not daring to advance. Such is the motion of the heart and pulse in animals. This type of motion, he goes on, must necessarily occur in all bodies that are situated in an intermediate state between suitability and unsuitability, with the result that, not being in their proper position, they strive to escape, are repulsed, and again continue to make the attempt. Even this brief account should suffice to furnish a general idea of Bacon's approach to the motion of the heart and the blood. On reading it one can understand why Harvey entertained a low opinion of Bacon as a scientist, observing on one occasion that he writes philosophy like a Lord Chancellor.[26]

Harvey's replies to Riolan are unrelated to his opinion of Bacon, though it may be observed that the Baconian account might have been more acceptable to a Galenist such as Riolan than it was to Harvey. The latter's first response to Riolan is a point-by-point reply to the criticisms voiced in the *Encheiridium*. It is mainly of interest for showing how deeply imbedded were Galenic notions in the medical profession of the time, and how patient Harvey could be in dealing with those who failed to comprehend his teaching. In it he tried to make clear how the principal use and end of the blood's circulation is to enliven all of the parts of the body. To explain this in terms more intelligible to Riolan, Harvey noted that physiologists see such parts as being sustained and actuated by inflowing heat and vital spirits. The mention of "vital spirits" seems to have caught Riolan's attention, for he sought to find in these a possible explanation of the blood's movement. This elicited from Harvey his *Second Disquisition to Riolan*, which is important for its evaluation of the role of vital spirits in causal explanations and for its remarks about

26. A contemporary, John Aubrey, is the source of this statement. See *Aubrey's Brief Lives*, ed. Oliver Lawson Dick, London: Penguin Classics, 1987, p. 213.

the completeness of such explanations. Both responses are contained in a book Harvey published in 1649 with the title *The Circulation of the Blood*, which he proposed in the form of two letters to Riolan. Whereas the first was a direct response to Riolan's book, the second is a more systematic treatise that was probably composed prior to the book's appearance, now published as though it were addressed solely to Riolan but actually replying to others among Harvey's critics.

In taking up the question of vital spirits, Harvey points out that their nature is very much disputed and that so many opinions have been voiced about them as to leave their nature wholly ambiguous. This makes them a refuge for persons of limited information, who, when at a loss to assign a cause for anything, commonly reply that it is done by spirits. Harvey then surveys the many kinds of spirits spoken of in medical schools, and points out how uncertain and questionable is the doctrine being proposed concerning them. His own view is that the spirits flowing along the veins and the arteries are not distinct from the blood, any more than the flame of the lamp is distinct from the vapor being burned in it. Earlier, in his treatise on animal generation, Harvey had insisted that there is no reason to search for spirits that are extraneous to, and distinct from, the blood itself. He had made the same point in his original discourse on the motion of the heart and blood, stating there that the blood and spirits are in reality but one body and not two distinct entities.

Notwithstanding the thoroughness of Harvey's causal analyses, he was quite prepared to admit that he did not have complete explanations, expecially in the matter of the final and efficient causes of the blood's circulation. Riolan seems to have touched on this matter, and Harvey saw in it an opportunity to reply to his and other's criticisms. His answer to those who repudiate the circulation because they do not know its extrinsic causes, that is, its efficient and final causes, is that the first question to be answered is the *an sit* of the circulation; only after this should one become concerned with the why of it or the *propter quid*. And to answer the first question one should make full use of the manifest data of the senses before resorting to rational speculations. Astronomers have to resort to reasoning because their objects of consideration are so remote from the senses, but this is not the case in the study of living organisms. For objects that come under the cognizance of the senses, Harvey asserts, no more certain demonstration can be adduced, nor is there any better means of gaining faith, than examination by the senses, what he calls ocular inspection. As to his demonstration of the circulation, therefore, the conclusion is true and necessary if the premises are true; and whether these are true or false only the senses can inform us, not any process of the mind.

Harvey's empiricism here is obviously not meant to exclude a further search for causes, but merely to determine the facts on which such a search can intelligently be based. For example, having established the fact of the blood's circulation, he was quite certain that the efficient cause of this circulation is the contraction of the muscles of the heart, that is, the heart's pumping action. What the further efficient cause of the pumping might be was not clear to him, although he discusses this type of question in the last part of his *Second Disquistion*. There he notes, without pretending to demonstrate it, that the rising and falling of the blood does not depend on vapors, or exhalations, or spirits, or any external agency, but simply on an internal principle under the control of nature. The "internal principle" to which he refers would be recognized by his contemporaries as the soul, or *anima*, the formal principle that satisfies Aristotle's definition of nature as the primary source of movement and rest in animated things.

With regard to Descartes' explanation of the circulation in the *Discourse on Method*, it was obvious to Harvey that Descartes had read his treatise but had not understood the demonstration that was offered in it. Instead, with his accustomed self-confidence, Descartes proposed his own demonstration and indeed claimed to know the "true cause" of the circulation. His mistake, Harvey points out, is precisely that against which he inveighed earlier in the *Second Disquisition*. Without having the facts straight, under the impetus of his rationalism he had indulged right away in fanciful speculation. Above all, he did not understand the difference between the heart's being in systole and its being in diastole, and not knowing this, he was unable to identify correctly the causes and effects associated with the two states. Then, as far as the efficient cause of the pulse is concerned, Descartes assumed that the cause of its systole is the same as that of its diastole, namely, an effervescence of the blood due to a kind of ebullition. There is no way, Harvey observes, that the quick strokes and percussions of the pulse can be caused by an ebullition or rarefaction, which are inherently gradual processes. It is obvious that Descartes was also wrong on his view of the heart as the source of heat, making the end or final cause of the circulation the conveyance of heat to the other members. Harvey does not comment on this explicitly, but he rejects it implicitly in his criticism of the ebullition process.

Harvey lived until 1657, almost thirty years after the publication of his demonstration. He had many friends among the scientific elite of his day, and his supporters were able gradually to overcome the opposition to his teaching. One of his friends, Thomas Hobbes, declared that Harvey was the only person he knew who had overcome public odium and established a new doctrine during his own lifetime.[27] And, for the most part, those who opposed him, like Descartes, did so because they lacked the patience or the skill to ascertain the facts on which the proof of the circulation was based. With regard to Riolan, however, a further point should be made. As we shall see in the next two sections, Harvey's search for the causes of the circulation terminated in much the same way as did Newton's searches for the colors of the spectrum and of gravity. Both Harvey and Newton employed induction and demonstration to establish what they regarded as certain conclusions, for which they proposed explanations through proximate and proper causes. Both realized that deeper and more ultimate causes might be involved, and yet they did not feel it necessary to uncover such causes before seeking assent to their conclusions, limited though these might be. In a word, their mentality was not: "Unless one knows everything, one cannot know anything." That would call for a God-like knowledge of nature, one very different from what humans are capable of acquiring. Yet that mentality is implicit in Riolan's questioning. With regard to efficient causality, Harvey was content to argue that the heart moves the blood, leaving aside the question of what it is that ultimately moves the heart. As to final causality, he saw the heart's purpose to be circulating the blood, leaving aside the question of what the ultimate purpose of the circulation might be. Thus he, and Newton in a different way, allowed the possibility of continued advance in scientific knowledge at the level of proximate causes, without requiring that every cause be known before a particular cause can be understood. The ideal of having the whole truth about nature need not deter one from seeking partial truths, to the extent that these are demonstrable with the resources available.

10.5 Experimenting with the Prism

As noted at the conclusion of Sec. 9.5, the results of Newton's *experimentum crucis*, like those of Harvey's ocular demonstration, were not accepted right off by scientists studying light and color in his day. The controversies the experiment provoked were connected not so much with his explanation of the elongation of the image projected from the prism as with the qualitative conclusions he drew from the experiment about radiant colors and their relationship to white light. Thus, having

27. Again John Aubrey is the source; see *Aubrey's Brief Lives*, p. 214.

explained the shape of the image, Newton went on to deduce from the experiment that colors are not qualifications of light deriving from refractions and reflections of natural bodies but are original and connate properties that differ from ray to ray. Some rays are disposed to exhibit a red color and no other; some a yellow and no other; some a green and no other; and so of the rest. This is true not only of the principal colors but of all their intermediate gradations. Moreover, not only are colors proper to the rays of which white light is composed, but the angle of refraction a ray experiences when passing through the prism is also a property that is immutably connected with the ray's color. In support of this further conclusion Newton states that the degree of refrangibility proper to a particular color cannot be changed either by refraction or reflection or any other process he has yet tried. Once he had separated a particular ray from the others, it henceforth retained its color despite all efforts to change it. As far as he could tell, therefore, he had discovered a true property of the rays that go to make up white light.[28]

Early Reactions. It is most interesting to study the various reactions evoked by the publication of Newton's first paper in the *Philosophical Transactions*. The general tenor of the responses was one of non-acceptance, and this because the respondents failed to comprehend the method Newton had used to establish his results. Criticisms were voiced by such eminent scientists as Robert Hooke and Christian Huygens, and by French and English Jesuits on the Continent who were under the influence of Grimaldi, who by this time was an eminent optician. All subscribed to a Cartesian system of explanation wherein they accounted for the various properties of light and color through one or another mechanical hypothesis. Newton, on the other hand, deliberately avoided such hypotheses, as he was later to avoid them in his explanations of gravity. On this account he was suspected of peripatetic tendencies, since he seemed to prefer qualities and "original properties" to the mechanistic explanations that had become popular throughout all of Europe.

As it turns out, Newton's critics were seeking explanations more ultimate than his, and so his constant response was that he was not committing himself on the nature of either light or color, but merely demonstrating properties of them that could be verified experimentally. Thus, when Hooke charged Newton with holding that light is a material substance, Newton replied that this was not his intention; rather he intended

28. *Philosophical Transactions* 80 (1671–1672), pp. 3081–3082.

to speak of light in general terms, considering it abstractly as whatever it is that is propagated in straight lines and in every direction from a luminous body. Precisely *what* it is he made no attempt to determine, allowing that it might be a confused mixture of difform qualities, or modes of bodies, or of bodies themselves, or of any virtues, powers, or beings whatsoever. And when he spoke of colors, he did so as these appear to the senses, regarding them simply as qualities of light external to the observer and thus capable of being studied through the use of experiment.[29]

Similarly, Huygens reproached Newton for not having hypothesized about the type of motion that produces colors. Insofar as he had not, Huygens argued, Newton had failed to teach the nature of colors and their kinds, despite his having discovered the important property of their different refrangibilities. To this Newton again replied that he never intended to show in what the nature and kinds of color consists, but only to show that, as a matter of fact, they are original and immutable qualities of the rays that exhibit them. He went on to explain that the most he would conclude about colors is that they themselves are basic and irreducible qualities. He would not attempt to explain their varieties in any deeper way, merely characterizing them through an effect or property that accompanies such qualities whenever they appear.[30]

More revealing for the present study are Newton's replies to the Jesuits who criticized his paper, possibly because he felt he could presume in them a better knowledge of demonstrative methodology. For example, the French Jesuit Ignace Pardies wrote to the Royal Society from the College of Clairmont in Paris about Newton's "very ingenious hypothesis" of light and colors, treating all of Newton's exposition as merely hypothetical. To this Newton replied immediately, disavowing that his theory was hypothetical in any way. Pardies thereupon answered that he had meant no disrespect, but that he had difficulties duplicating the experiment and thought the results alleged might be explainable without recourse to Newton's "true cause." Pardies wondered in particular whether they could be reconciled with one or another mechanical hypothesis, such as those of Grimaldi, Hooke, or Descartes. This again evoked a disavowal by Newton, denying that his experiment had any connection with hypotheses. The best and safest method of philosophizing, he wrote Pardies, is first to establish the properties of things by experiments and then to proceed more slowly to hypotheses for their explanation. If one starts with hypotheses, one will never attain certainty

29. *Philosophical Transactions* 88 (1672), p. 5086.
30. *Philosophical Transactions* 96 (1673), p. 6086; 97 (1673), p. 6109.

in any scientific endeavor, for more and more hypotheses can always be devised as difficulties present themselves. Pardies seems to have been satisfied with this, for he thanked Newton for the additional information he had supplied about the experiment, noting that when he performed it again in light of that information everything turned out as Newton had claimed.[31]

Of similar interest is Newton's interchange with two British Jesuits who were then teaching at the English college in Liège, Francis Line and Anthony Lucas. Line had started the controversy with Newton in 1674 when he was professor of physics there, and Lucas continued it when he succeeded to the post on Line's death. A meticulous experimenter, Lucas wrote to Newton in 1676 of the difficulties he was experiencing with the *experimentum crucis* and suggested to Newton that he should perform other experiments. Newton thanked Lucas for being the first to inform him of the detailed "experimental examination" of his work but declined to go into the matter of other experiments. "For it is not number of experiments, but weight to be regarded," wrote Newton, "and where one will do, what need many?" Lucas had presumed that Newton had not performed enough experiments, but he should have focused attention first on those already performed, for "if any of those be demonstrative, they will need no assistance, nor leave room for further disputing about what they demonstrate." Lucas's basic problem seems to have been the different refrangibility of light. This, Newton explained, is what he had already demonstrated by the *experimentum crucis*. "Now if this demonstration be good," he went on, "there needs no further examination of the thing; if not good, the fault of it is to be shown: for the only way to examine a demonstrated proposition is to examine the demonstration."[32]

The Optical Lectures. This is one of the clearest statements by Newton of the demonstrative character of his experimental work, similar in many respects to Harvey's claims about his demonstration of the motion of the heart and blood. In the course of the response to Lucas, Newton mentioned that he had in fact performed many experiments, including those Lucas was suggesting to him, and had actually written a tractate on the subject. This tractate was probably his *Optical Lectures*, delivered at Cambridge between 1670 and 1672 as his inaugural lectures as

31. *Philosophical Transactions* 84 (1672), pp. 4087–4090, 4093; 85 (1672), pp. 5013–5014.

32. *Philosophical Transactions* 128 (1676), pp. 702–704.

Lucasian professor of mathematics; these he then revised, depositing an alternate set in the University Library in October of 1674. The lectures have recently received attention in the literature, first by Alan Shapiro for their optical teachings and then by Simon Schaffer for what they reveal about the prisms and the experimental arrangements Newton actually used.[33] Both studies cast additional light on Newton's claims for the apodictic nature of the *experimentum crucis*.

One of Shapiro's main emphases is that one should be clear on what the *experimentum* was intended to prove. This is not that colors are innate to white light before any refraction; rather it is that the sun's light "consists of rays" of unequal degrees of refrangibility. But in the "New Theory" letter in the *Philosophical Transactions* Newton ties the innateness and immutability of colors directly to the innateness and immutability of their degrees of refrangibility. Apparently what he had in mind was an argument that proceeds as follows. If the colors of light rays are absolutely immutable, and if the rays exhibit some color after refraction, the rays must have been disposed to exhibit that same color before refraction; therefore the colors are innate to the sun's direct light, even though they are not apparent before the first refraction. The force of the argument obviously depends on the precise meaning one attaches to the expression "consists of" when saying that the sun's light thus consists of colored rays. One way of understanding this would be in terms of a corpuscular theory of light to which Newton was already committed, which could attach colors to different types of corpuscles. Then, if the corpuscles were present as rays in white light, the colors would be present there also. But to offer this explanation Newton would have to resort to a hypothesis, namely, a mechanical theory of the composition of light, which he was resolutely opposed to doing. Another way of understanding his argument, however, would be to invoke a scholastic view of presence that would be intelligible to a Jesuit such as Lucas. This would be to say that the component rays of colored light are indeed present in white light, but they are there not actually, or potentially, but virtually, the way elements were then said to be present in compounds. An empiricist theory of knowledge might not countenance such an infer-

33. Alan E. Shapiro, "The Evolving Structure of Newton's Theory of White Light and Color," *Isis* 71 (1980), pp. 211–235, and Simon Schaffer, "Glass Works: Newton's Prisms and the Uses of Experiment," in *The Uses of Experiment: Studies in the Natural Sciences*, ed. David Gooding, Trevor Pinch, and Simon Schaffer, Cambridge: Cambridge University Press, 1989, pp. 67–104. See also Shapiro's "Newton's Definition of a Light Ray and the Diffusion Theories of Chromatic Dispersion," *Isis* 66 (1975), pp. 194–210.

ence, but it would be intelligible, and have demonstrative force, within an Aristotelian framework.

Schaffer's study of Newton's "glass works" is quite different from Shapiro's, for Schaffer focuses on a sociological rather than on an optical theme, namely, how experiment, and particularly a crucial experiment, is used to establish authority in a scientific dispute. The interpretation of the prism experiments, on his view, was really an issue of instrumentation. On the question of what makes an experiment self-evident, transparent to those to whom it is proposed, Schaffer would therefore answer: good prisms. Newton had access to good prisms, and in this his situation was quite like that of Galileo, who had access to good telescopes. Unfortunately Newton gave insufficient instructions for the audience to whom the *experimentum crucis* was presented, for he himself had drawn on the rich store of subsidiary experiments he performed in conjunction with his *Optical Lectures* at Cambridge. And not only did the audience lack instructions, but generally they were operating under a philosophy different from Newton's. It took a while for dissenting scientists to be convinced, and it was only with the publication of his *Opticks* in 1704 that Newton ultimately achieved his objective. That was in London, however, and there were still dissenters in France and in Italy. As Schaffer portrays the scenario, there was a considerable amount of social construction in Newton's victory in England. But unfortunately, in elaborating the details he needs to make his case, Schaffer loses sight of Newton's arguments and, perhaps inadvertently, accords no weight to the demonstration Newton claimed to have offered. In effect, Schaffer disregards its apodictic status and treats it merely as a dialectical argument, persuasive not on its intrinsic value but only on the weight of the public authority Newton and his supporters had brought to bear on the issue under dispute.

A more extreme sociological view of Newton's achievement is that of Alan Gross, a proponent of the so-called "radical rhetoric of science," a movement whose aim is to show that all science is nothing more than rhetoric.[34] An English teacher himself, Gross argues that since the paper in the *Philosophical Transactions* failed to convince, Newton went through a "rhetorical conversion." He changed his style completely from what he had offered in the "New Theory," so much so that the *Opticks* he ultimately produced, in Gross's eyes, became a "rhetorical masterpiece." Gross arrives at this judgment from a study of what he identifies as

34. See his *The Rhetoric of Science*, Cambridge, Mass.: Harvard University Press, 1990, pp. 111–128.

rhetorical devices in the latter work: use of arrangement (Euclidean deduction), of presence (multiple experiments), and of rhetorical questions (the Queries at the end). Few scholars will agree with the understanding of rhetoric implicit in these examples, for Gross is clearly unable to differentiate rhetoric from dialectics, to say nothing of demonstrative science. As to his knowledge of optics, he gives no evidence of having acquired the *endoxa* necessary to understand and pass judgment on Newton's claims. Yet Gross does offer a dramatic instance of the difficulties inherent in presenting a scientific argument to a universal audience, since inevitably such an audience will include many who are either incapable of grasping, or unwilling to grasp, its demonstrative force.

Newton, on the other hand, did have success among his contemporaries, not only with the *experimentum crucis* but also with the *Opticks*. In the first he discovered a basic truth about chromatic dispersion, granted that this is a far more complicated phenomenon than the simplified account in the "New Theory" would have led one to suspect. He presented a fuller version of the truth in the first two books of the *Opticks*, but surely did not exhaust the subject there, as he himself was aware. The observations and queries of the third book then stimulated others to explore yet further truths about optical phenomena, in a quest that remains still unended to the present day.

10.6 The Cause of Gravity

Newton's *Principia*, as noted at the end of Sec. 9.6, met with much the same initial reaction as did his first paper in the *Philosophical Transactions*, and for much the same reason. In 1687 practically the entire scientific community, in England as on the Continent, had become captive to Descartes' mechanical philosophy. Just as it was then common to think of light as the motion of small, rotating luminiferous particles, so it was then common to think of planets being propelled toward the sun by vortices in the celestial aether. The universe was thought to be a plenum, and motion toward a center was seen as effected by a push from behind the moving body. Now Newton's new focus was on the body that moved, not on what moved the body. His emphasis therefore was not on a particular physical agent that might move a body toward a center, but rather on something within the body that would serve to explain its motion, namely, the body's gravity. Unfortunately, as he put it, he introduced the term "attraction" into his discourse to make himself "more easily understood by mathematical readers." Non-mathematical readers found that term very appealing too, with the result that the notion of gravity was soon displaced, in the minds of many, by the notion of attraction. Instead of gravity, therefore, the problem became the pull of gravity, and this provoked a controversy that lasted for almost a century. But it was not gravity itself that was the subject of controversy; rather the cause of gravity was the issue on which it centered.

Both Huygens and Leibniz reacted predictably in the Cartesian manner. Huygens could see gravity as nothing more than the effect of an extraneous action. He still held for vortices, but his were quicker of movement and smaller than Descartes', so allowing for greater distances between them. The basic conception was one Descartes had used to explain gravity as experienced on earth, namely, some fluid matter moving away from its center and so causing other matter to move toward it. Leibniz subscribed to a similar notion, though he claimed to have taken his inspiration from Kepler. On this account he referred to the motion of the planets around the sun as a "harmonic circulation." His general principle was that all bodies that describe a curved line when in a fluid are carried along by the motion of the fluid. From that principle he proceeded to deduce Kepler's laws of planetary motion, claiming that the planets' paths are determined by fluid orbs in the aether, but never explaining, as Koyré has observed, why the fluid orbs move precisely as they do. Leibniz also attributed a "paracentric" motion to the planets wherewith they counteract the centrifugal component of their circulation by an "attraction" toward the sun. This attraction he called the "solicitation of gravity," but in truth, he said, it should be called an impulse, since it derives from impulses imparted to the body by the circumambient fluid.[35]

Leibniz is more celebrated for his opposition to Newton on the ground that gravity is an occult quality. For this he had recourse to a theological argument: God does not attribute to bodies qualities that cannot be understood. Anything claimed to be performed without a mechanism falls into this category and so is unreasonable. On this basis gravity is an "unreasonable occult quality," one that could not be explained even by God or an angel. Roger Cotes, Newton's friend and editor of the second edition of the *Principia*, responded that gravity is not an occult cause, for it is plain from phenomena that such a power exists. An occult cause would rather be one such as Newton's adversaries had alleged, namely,

35. For details and documentation of Huygens' and Leibniz's views, see Alexandre Koyré, *Newtonian Studies*, Cambridge, Mass,: Harvard University Press, 1965, pp. 115–138.

imaginary vortices that are not only imperceptible to the senses but in fact are entirely fictitious. Moreover, gravity is a primary property of bodies, and such attributes need not depend on others or have prior mechanical causes. Newton himself recognized that Aristotelians refer to some qualities as occult, but, he said, by that they meant qualities that lie hidden in bodies and so are the unknown causes of manifest effects. Newton rightly perceived that, in the Aristotelian view, such qualities were thought to flow from the natural or substantial forms of inorganic substances, what he referred to as "Specifick Forms."[36] But apparently he had forgotten that for Aristotle all proper qualities or natural powers, and not only those that remain unknown, flow from natural or specifying forms, as has been explained in the first chapter of this volume.[37]

Much of the difficulty in ascertaining what Newton himself meant by gravity is occasioned by a statement he made in explicating the third rule of his Rules of Philosophizing (Sec. 9.6). There he refrains from affirming that gravity is essential to bodies, on the ground that their gravity diminishes as they recede from the earth. Obviously a power can be natural, and in this sense proper or essential, even though it produces variable effects in different circumstances. It is thus understandable why Newtonians had great difficulty understanding what Newton could have meant by this and similar statements. Some, such as Cotes, sought to avoid the difficulty by calling gravity a primary quality rather than an essential quality. Others, such as John Locke and Samuel Clarke, thought of gravity as a power put into matter by God and thus the result of an immaterial cause. Clarke, in particular, denied that gravity could proceed from the "Specifick Forms" of bodies. Since it is always proportional to the quantity of solid matter in a body, he argued, it must be traceable to some cause that penetrates into the very substance of solid matter and so itself is immaterial. In Clarke's view, every particle of matter gravitates to every other particle in the universe, all being impelled to each other by gravity, ultimately under the action of the First Cause.[38] For a Christian theologian such as Clarke, of course, this is not saying much, since every action in the universe ultimately would come under the divine causality. The problem is not with the ultimate cause but with the proper

36. Ibid., pp. 139–148.

37. As is evidenced by his Trinity Notebook, Newton had a surprisingly good knowledge of Aristotelian physics; for some significant excerpts, see my "Newton's Early Writings: Beginnings of a New Direction," in *Newton and the New Direction in Science*, ed. G. V. Coyne et al., Vatican City: The Vatican Observatory, pp. 23–44.

38. Ibid., pp. 149–163, 170–172.

cause, and this could now be seen as a separate power, a *vis gravitatis*, shown by Newton to be pervasive throughout the known universe.

These few opinions on gravity and its cause, and they could be augmented by many more, show how difficult it was for Newton's contemporaries, in England and elsewhere, to comprehend the demonstration he had offered for gravity being universal throughout the cosmos. He himself felt that he had sufficiently established the existence of gravity and did not feel it necessary to demonstrate its cause. In any event he was unable to do this by experimental means, and he did not wish to introduce hypothetical entities into his discourse, as many of his critics were intent on doing. It could be that many of his readers, not understanding the demonstration, remained unconvinced that all matter in the universe is ponderable or has gravity. For them, then, celestial matter would have continued to be very different in kind from terrestrial matter, as it had been for the ancients. When, then, was universal consensus reached on the subject of gravity? Or is belief in gravity, at least within our solar system, still a revisable option, a matter on which one can have only opinion even in the present day?

However one answers this, it would seem that within a century of the publication of the *Principia* most physicists were convinced by Newton's arguments. But such conviction would not be a hindrance to anyone's entertaining the general theory of relativity, when this was proposed by Einstein in 1915, as an alternate explanation of gravity's cause. By then scientists were less adverse to hypothetical explanations than was Newton, but at least, thanks to him, they had the fact of gravity firmly in hand before conjecturing once again about its hidden cause.

10.7 Quantifying Qualities

Newton had great success in making color become mathematical, as also in showing how the existence of gravity could be known through simple techniques of indirect measurement with the aid of the telescope. He suspected that there were yet-unknown forces associated with electricity and magnetism, and soon after his death, the existence of such forces would become evident through the work of other investigators. The discovery of atoms and molecules would have been impossible without knowledge of these occult qualities or forces. In reciprocal fashion, knowledge of atoms and molecules, once attained, would quickly shed light on the more common qualities, those discernible in sense experience and called manifest or sensible qualities to distinguish them from the hidden or occult. Discussion in the previous section focused on speculation about the cause of gravity, but more fruitful areas of research are those concerned with the causes of manifest qualities and of atmospheric displays such as the aurora borealis. Sense phenomena such as these involve qualitative changes that can be investigated through the use of quantitative techniques. As we have already intimated in Sec. 4.8, their study has led to fuller knowledge of the nature of sound, heat, and color, and how these qualities in turn are related to the molecular, atomic, and subatomic components of the bodies in which they appear. A brief overview of this development may now indicate how, through the use of measuring procedures, one can regress from sensible qualities to the quantitative modalities that underlie them, and then, through the use of metrical middle terms, return by way of causal explanation to the qualities themselves.

Sensible Qualities. To speak of the nature of sound or other sensible quality is to seek its definition, and this is best given in terms of the causes of the quality's production. As explained in Sec. 1.7, qualities are accidents, as opposed to substances, and on this account they are defined differently than substances. For example, the matter or material cause of a substance is part of that substance, whereas the matter or material cause of an accident is not part of the accident but rather its appropriate subject, the substance in which it exists. Similarly, the formal cause of an accident is the precise effect or modality the accident introduces into the subject or substance by its presence. To investigate this, one first considers the subject without the accident, then determines the proper extrinsic agent or efficient cause that produces the accident in the subject, and from this ascertains precisely what new effect or modality exists in the subject as a result of the accident's presence. The method is that of defining an accident through its proper effect, effect being taken here in the sense of primary formal effect and not simply the action produced by an agent (see Secs. 7.8 and 9.2). The accident is thus defined through the process of its production, dynamically rather than statically, and in this context it is a relatively simple matter to identify the four causes involved.

Applying this method to the study of sound, the final cause of a sound's production is its generation in some subject, ultimately its sensation in a hearing subject, while the efficient cause is the agent that produces it. The material cause is the medium that is capable of supporting sound and in which it is generated, and the formal cause is the modality introduced into the medium, for example, a type of regular vibratory motion. Obviously there is a close interrelation between sound's material and formal causes, since the medium must have parts capable of supporting the type of vibratory motion induced, say, relatively large masses of molecules that can readily be set in motion. The agent will usually be some type of resonator that can displace the medium and maintain it in regular mechanical vibration. As for the final cause, since sound is thought of as a quality perceptible to the sense of hearing, the term is applied most properly to vibrations in the audible range. But once the peculiar quantitative modality of audible sound has been ascertained, the term can be applied to vibrations in the subsonic and ultrasonic regions as well. And, should one be concerned whether there is the sound of a falling tree in a forest when no one is there to hear it, an answer can be given in terms of its formal and its material causes. Sound is not formally present in the forest when it is not heard, but it is materially present as long as the vibratory motion caused by the falling tree continues in the atmosphere.

The same procedure can be used to define heat through the four causes of its generation. As in the case of sound, the final cause is its perception by the appropriate sense organ, here basically the sense of touch. The efficient cause is electromagnetic radiation in the infrared portion of the spectrum or a mechanical motion such as generates friction. The material cause or subject in which heat properly exists is a physical body whose microstructure is such that its parts are susceptible to random motion. The particular modality heat introduces into this subject is a motion that is more irregular than that associated with sound and also of smaller amplitude. As opposed to a bulk movement of the medium, this is essentially a random molecular movement. It may be either a translational motion of entire molecules or vibratory and rotary motions within molecules themselves on the part of their constituent atoms. Temperature differences in heat are then a function of velocity distributions of individual molecules, whereas thermal capacity or specific heat is associated with the internal degrees of freedom within molecules dependent on the particular state of the substance, whether this be gaseous, liquid, or solid. Any body having parts susceptible to random motions of this type is the material cause of heat, while its formal cause is the actuation of that particular susceptibility.

The sensible quality of color, related as this is to light, is more difficult to define causally. Through the researches of many investigators culminating with James Clerk Maxwell (1831–1879), however, it was found that, as Maxwell explained in 1864, light consists in the transverse undulations of the same medium that is the cause of electric and magnetic phenomena. In other words, the nature of light, on which Newton refused to speculate, was now recognized as electromagnetic radiation in the visible portion of the spectrum. When illuminated by light, the color in an opaque surface becomes sensible to sight, just as sound is sensible to the ear and heat to touch. The efficient cause that renders color existent and visible is thus light, whose source is a radiant body. This is basically a substance whose atoms are excitable, that is, they contain electrons that can be moved to a higher energy state from which they return to their normal or ground state and emit, in the process, rays of particular wavelength referred to as colored light. These rays are not themselves colored, but they have the ability to make visibly colored any surface containing this color at least virtually. The material cause, or the proper subject in which color is found, is a surface or volume that is capable of selectively scattering and reflecting some particular wavelength distribution to the eye. This capacity to absorb and selectively scatter incident radiation is a function of the molecular structure of the surface, wherein the molecules and their electrons respond in a selective way. The formal cause of color is then the actualization of such a capacity or ability in the molecules of the surface being illuminated. When this potency is actualized, the body is actually colored, and is so seen by the eye. From this explanation, it should be clear that one cannot specify the color of an object without reference to the light under which it is viewed. Similarly, if one questions whether colors exist in darkness or in the interiors of objects, answers must be given in terms of the distinctions just made between the formal and the material causes of color. Colors do not exist formally in darkness or in the interior of objects, because there they lack the light by which they become actually visible. They are present materially, however, when the structure of the surface is such that it is capable of reflecting colored rays to the eye, should they be illuminated by a proper light source.

Metrical Aspects. All of these qualities, sound, heat, and light or color, can be subjected to measurement, as explained in Sec. 7.1, and thus they can be made mathematical, as Newton foresaw. Not only can causal definitions be given of them, but from such definitions and the quantitative modalities associated with them demonstrations can be formulated and true and certain properties deduced—analogous in many respects to those deduced by Newton from his *experimentum crucis*. Such demonstrations provide the content of the sciences, each of them branches of physics, known in the present day as acoustics, thermodynamics, and optics. In their abstract formulation these sciences may seem far removed from sensible qualities, and yet such qualities are their proper subject. If human beings, or terrestrial animals of which humans are a species, were deprived of the senses of sight, hearing, and thermal sensitivity, there would be no starting points from which to elaborate these sciences. By the same token, it would be very difficult to achieve any scientific knowledge of nature as a whole. Observational terms would be drastically reduced in number, and the empirical bases of all other sciences, but especially the life sciences, would become vanishingly small.

Causal definitions of sensible qualities also lead to simple corollaries relating to the quantitative foundations required for their presence in particular types of bodies. As accidents, qualities are rooted in the substances they modify as accidental forms, but sensible accidents are peculiar in the sense that they are rooted in science through the intermediacy of quantity—*quantitate mediante*, to use the Latin expression. As a consequence there is a type of ontological hierarchy in the ordering of sensible qualities. The proper subject of sound, as has been seen, is a medium or entity with parts that are susceptible to regular vibratory motion. This requirement automatically limits the existence of sound to subjects large enough to include macroscopic domains of molecules that can support such motion. Likewise, the proper subject of heat is an entity with parts susceptible to random motion in one or more degrees of freedom; under this requirement, heat can exist only in aggregates of atomic particles and not in the individual atom as such. Again, the proper subject of color is an entity whose electronic structure is capable of a particular type of electromagnetic resonance. Thus it does not make sense to attribute color to an entity that cannot possess such an electronic structure, as, for example, the electron itself.

The application of this line of reasoning to current problems in the philosophy of science should be obvious. If one cannot speak of a *red* electron, or a *hot* atom, or a *noisy* molecule on the basis of the definition these attributes, one should be even more wary of assigning conventional attributes to entities at the level of the so-called elementary particles. The ontological hierarchy just explained demands certain minimum quantitative dimensions for the existence of sensible qualities, with color preceding heat and heat preceding sound in their dimensional requirements. Beyond these minima, even though quantified matter might be present, it cannot be endowed with the corresponding qualitative attributes.

Quantitative dimensionality, in this understanding, becomes the material cause of sensible quality. One might push such an inquiry further and ask for the material cause of quantitative dimensions themselves. If quantity is prerequisite to, and in a certain respect serves to explain, the presence of sensible quality, is there something ontologically prior to quantity which is prerequisite to, and serves to explain, such realities as mass, length, and continuous motion? No less a physicist than Werner Heisenberg has raised this question and answered it in the affirmative. He regards such a prior ontological subject as necessary, and identifies it, surprisingly enough, with the protomatter discussed at the outset of this work (Secs. 1.2, 2.5). Such a concept, for him, offers the only realist solution to the enigmas posed by the principles of uncertainty and complementarity. These prohibit one not only from applying conventional attributes, including those of classical mechanics, to elementary particles, but even of speaking of their proper parts as though such particles could be divided into smaller bits. Quality is explained, as through a material cause, by quantity, and quantity is explained, on the same basis, by a material principle of substance that exists only *in potentia*.[39]

But this restriction on predication also implies a further restriction on the ability of the quantum physicist to attribute natures to elementary particles. Scientists recognize many natures in the universe, those of chemical substances, of plants and animals in all sizes and great variety, even of planets and stars, to the extent that these can be said to have natures. What is important to note is that invariably they do so on the basis of sense experience. They first come to know sensible qualities, sense data, either in themselves or indirectly through measurement, for these function as their empirically givens, the observational and metrical terms on which they base their reasoning. But particle physicists, bereft of sense data in the ordinary sense, must access the subatomic world with forces or powers that resemble the occult qualities of the medievals more than they do the manifest qualities through which they understand the rest of the universe. This clouds the intelligibility of their quantum world and makes it extremely difficult for them to arrive at any knowledge that qualifies as epistemic. Yet quantum mechanics is not the whole of science, and, whatever the limitations under which it works, these should not be construed as applying to the entire scientific enterprise.[40]

39. Werner Heisenberg, *Physics and Philosophy*, New York: Harper and Brothers, 1958, pp. 41, 53, 70, 73, 110, 160, 166, 180–186. For Heisenberg's general endorsement of the views expressed in my "Elementarity and Reality in Particle Physics," see the interchange of correspondence between him and Prof. Gora in *Boston Studies in the Philosophy of Science* 3 (1968), pp. 257–259, reprinted in *From a Realist Point of View*, 2d ed., pp. 206–208.

40. No attempt has been made in this study to address the subject of quantum anomalies, since these presume technical competence beyond what can reasonably

10.8 The Modeling of Nature Revisited

With this we have finally rejoined the discussion initiated in the first part of this volume. It would be fruitless, and practically impossible, to list the major demonstrations on which the models of various natures described in our first five chapters are based. In the present chapter and the one preceding we have sketched but a handful of demonstrations, along with the controversies to which they gave rise. The first of these was proposed before 1311 and the last in 1953. In between were five from the period between 1610 and 1678 and one from about 1860. All are important for having laid foundations on which the modern sciences of optics, astronomy, mechanics, biology, and chemistry are based. Some gained the almost universal assent of other scientists within a year of their formulation, others took decades before they were accepted. There is no reason to suspect that these are unrepresentative in this respect, even though a few were very revolutionary in the doctrines they were advancing.

Earlier it was stated that what most people know about the universe in which they live is opinion, and yet most of what they know is true. With a few changes this statement can also be applied to scientists. The controversial aspect of scientific growth is confusing and troublesome when viewed in the short term, but it does have a purifying and solidifying effect on the knowledge that ultimately accrues within a discipline. It may be the case that science educators tend to obliterate the tortuous path by which results are arrived at. This is to be expected, for the volume of knowledge they have to communicate is so vast that they can be excused for not tracing the many detours in their discipline's history. But by and large, science textbooks at the college level do a remarkably good job of providing the fundamentals, and those at the graduate level do the same for specialization within a field. Those who have completed doctoral comprehensives can thus be expected to know all that is known with certitude or with a high degree of probability within their specialities, and generally to have reputable opinion in neighboring fields. Professors who direct dissertations at the doctoral level are the best guides to when "the book is closed" within a particular area of research, for their task is to orient their students toward the unknown or the poorly understood, not simply to repeat work that has already been done.

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be expected of the general reader. A recent work that takes account of such knowledge and offers solutions that are consonant with the Aristotelian-Thomistic perspective here adopted is that of Wolfgang Smith, *The Quantum Enigma: Finding the Hidden Key*, Peru, Illinois: Sherwood Sugden & Company, 1995.

Implicit Demonstrations. With regard to demonstrations, these are continually being offered in the scientific literature, although rarely are claims made for their apodictic character. Most of these are *quia* demonstrations, demonstrations "of the fact," though in many cases they are quickly followed by *propter quid* demonstrations, those "of the reasoned fact." Again, no longer do they come from the individual scientist who is the sole judge of whether or not to present his results to others. Rather they come from teams of scientists who are checking and cross-checking results, in constant communication with teams working on similar problems, and this on both the national and the international scene. Such collaboration and certification does much to diminish controversy and to accelerate the growth of scientific knowledge over what it has been in the past.

The demonstrative regress that was used so effectively by Galileo and Newton, and which involves a concatenation of *quia* and *propter quid* demonstrations, continues to be the main vehicle for this growth to occur. The experimentalists, those who discover various hitherto unknown effects that require explanation—in atomic physics, the Zeeman effect, the photoelectric effect, the Compton effect, the Stern-Gerlach effect, the "scattering" of alpha particles, etc., all discovered between 1896 and 1924—generally supply the *quia* demonstrations. Theoreticians, mainly mathematical physicists—and here the names of Bohr, Sommerfeld, Heisenberg, Schrödinger, and Pauli, all working over roughly the same period, suggest themselves—then supply the *propter quid*, mainly on the basis of convertible predications in their mathematical formulations. This assumes, of course, that modeling techniques are fruitful in providing quantitative analogies and that analogous middle terms can be employed in demonstrative syllogisms, as already explained in Sec. 8.4.

Conjectural reasoning is obviously employed in the dialectical processes that lead to demonstrations of this kind. Most philosophers of science focus on this and characterize it as hypothetico-deductive reasoning along the lines sketched in Sec. 7.3 above. The difficulty with this way of viewing scientific argument is that it practically excludes from the outset the possibility of attaining truth with certitude, a possibility that scientists surely would like to keep open in their investigations. The alternative way of dealing with hypotheses is that of introducing them as suppositions (Lat. *suppositiones*) in the intermediate stage of the demonstrative *regressus*, as explained above in Secs. 8.5 and 8.6. Unlike the type of demonstration *ex suppositione* that was found objectionable by Bellarmine in defenses of the Copernican system (Sec. 10.3), this use permits the suppositions to be verified within the demonstrative process through simple *a posteriori* reasoning. Examples of this technique have been provided in the analyses of Galileo's work with the telescope and his experiments with falling bodies given above in Secs. 9.2 and 9.3. This usage allows one to verify particular suppositions within the degree of accuracy to be expected in nature, without requiring confirmation of global theories as these are sought in HD methodology.

Newton's *Principia*, along with similar systematic expositions, poses a slightly different problem, in that the suppositions on which the system is based are not stated as such. In Newton's case, it turns out that these are embodied in the definitions he provides at the very beginning of the work and in the explanations he provides of the laws of motion. Throughout the *Principia*, moreover, he makes statements that tie the propositions he deduces to various experimental data that provide evidential supports. In this way, as Clark Glymour has argued, it is possible to understand the *Principia* as an interlaced series of propositions one part of which provides confirmation for another by a process he calls "bootstrapping."[41] Glymour applies this technique to show how Newton gives indirect confirmation for universal gravitation, thus verifying the demonstration that has been presented in a more intuitive way in Sec. 9.6 above. Had this way of understanding the *Principia* been commonly grasped early in the eighteenth century, much of the controversy surrounding that work might have been avoided. Most scientists who saw in the Newtonian system proof of the earth's motion probably read the *Principia* in this or a similar way. Others clearly did not, nor did most non-scientists, who could not grasp its demonstrations because of the mathematics involved. The result was that the earth's motion could still be regarded as problematic throughout most of that century, as already noted in Sec. 10.3.

Modeling of Natures. To return to the modeling of natures presented in Part I above, these are intended to portray in a general way the accumulated knowledge of nature to which scientists or those with reputable opinion about science would give assent as true or highly probable. Being couched in general and qualitative terms, in the "confused" way in which sense knowledge is commonly certified, they should appear to the general reader as uncontroversial. After the initial presentation of what is meant by the Aristotelian concept of nature and the causal context in

41. In his *Theory and Evidence*, Princeton: Princeton University Press, 1980, pp. 110–175.

which it is understood, models of various natures have been presented in what may be called an evolutionary sequence. This started with inorganic natures in Chap. 2, continued with plant and animal natures in Chap. 3, and concluded with human nature in Chap. 5, with an intermediate discussion in Chap. 4 of the modeling of mind, the first part of which pertained to animal nature and the second to human nature. This order actually violates the ideal epistemologial sequence of proceeding from the more known to the less known, since we obviously know much more about human beings than we do about elementary particles. Yet this way of exposing the subject matter of a philosophy of nature turns out to be a desirable propaedeutic for an analysis of contemporary philosophy of science. Oddly enough, it also mirrors the way in which the *corpus aristotelicum* has been organized in the Bekker Greek edition of Aristotle's works.

Central to the exposition of the generic natures, inorganic, plant, and animal, plus the one specific nature, human nature, is the concept of power, which is the warrant for our referring to the schemata for these as powers models. The extraordinary thing about human nature is that it includes within itself all of the powers found in the animal, plant, and inorganic kingdoms. Thus, by reflecting on oneself, one has a privileged insight into the whole world of nature. And, although in a pedagogical order it seems desirable to introduce powers models in a sequence of increasing complexity, there are advantages in considering these models in the reverse order, from the top down, as it were. Knowledge of human nature casts light on animal natures, that of animal natures does the same for plant natures, and that of plant natures, for the inorganic. The interrelationships within the entire order of nature thus suggest another type of "bootstrapping" wherein our understanding of one part of nature casts light on, and both reinforces and certifies, our understanding of other parts. And, contrary to a common view in the present day, this way of conceptualizing science does not put physics or the physical sciences in a privileged position vis-à-vis the biological or the human sciences. All sciences stand on an equal, and complementary, footing. The precision, and simplicity, of mathematical reasoning is very satisfying when one deals with the theoretical entities with which physicists are mainly concerned, but the mathematical approach suitable to their domain leaves out much that is readily intelligible to naturalists and humanists.

When these considerations are taken into account, the full modeling of human nature to flesh out all the powers of the human soul presents itself as a daunting task, one that will not quite fit on a two-dimensional drawing such is shown in Fig. 5.1. But there is an alternative to the two-

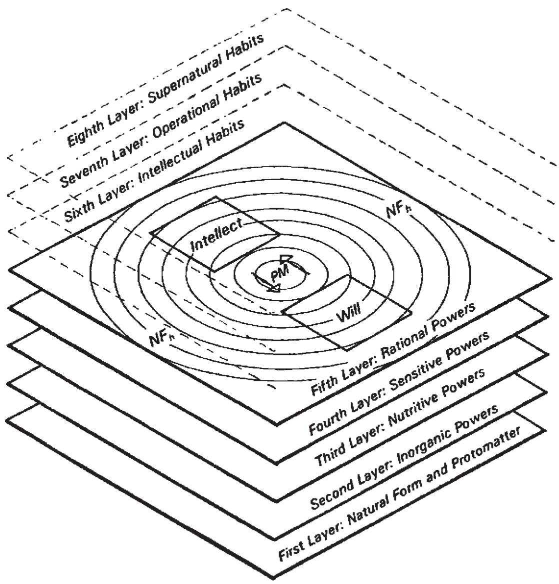

Fig. 10.1 An Overlay Model of Human Nature

dimensional approach, one that is incorporated in computer graphics programs such as AutoCAD. This allows for models or schemata being prepared as layers that can be overlaid one on the other to specify in ever more detail the reality being modeled. In plans for a house, for example, the bottom layer might be the foundation, the second the floor plan, the third the plumbing plan, the fourth the wiring plan, the fifth the heating and cooling, and so on. The layers are like transparencies that can be shown individually, or superimposed one on the other, all together or in various combinations. Employing that technique, the powers model of human nature depicted in Fig. 5.1 may be redrawn, now without some of the detail so as to eliminate the clutter, and then redistributed in the five layers shown in the lower front part of Fig. 10.1. Here the first, or bottom, layer might well be the basic model of protomatter PM being expanded by natural form NF as an energizing field (Fig. 1.4). Above that, the second layer would be the powers within that field proper to inorganic forms NF_i (Fig. 2.6), the third those proper to plant forms NF_p (Fig. 3.5), the fourth those proper to animal forms NF_a (Fig. 3.10), and the fifth those proper to the human form NF_h (the powers drawn in double outline in Fig. 5.1). But one need not stop there. Additional layers could be added to provide for the perfectibility of the human intellect and will, as already suggested in Fig. 5.5. How this might be accomplished is indicated in dashed outline in the upper rear part of Fig. 10.1. Here the sixth layer might be reserved for intellectual habits, the concepts and sciences that perfect the intellect, and the seventh layer for operational habits, found principally in the will. And, for the sake of completeness, one could add an eighth layer to provide for the entitative habit of divine grace and the supernatural habits it brings to the human soul. This was Thomas Aquinas's distinctive contribution to medieval theology in the Second Part of his famous *Summa theologiae*, where he set himself to show not only that grace perfects nature, but that the nature it perfects is the same human nature that actualizes protomatter, the most perfect natural form to be found in the universe.[42]

10.9 Philosophy of Science: A Reprise

What advantages would a philosophy of science based on the Aristotelian concept of nature have over the empiricist philosophies of science that have been dominant in the discipline to date? The answer to this question is implicit in much of the discussion throughout the second part of this volume, particularly in the theme set in Sec. 6.8 and then elaborated in its remaining chapters. Now, at this point, in bringing the work to conclusion, it seems well to reflect on the import of that discussion for a definition of the philosophy of science and for exploring why it may be desirable to study that discipline in the late twentieth century.

Most of those who speak of the philosophy of science do not advert to what the term "philosophy" in that expression means. What it usually means is logical empiricism, with the added but implicit supposition that the rise of modern science has rendered all other philosophies, and particularly Aristotelianism, obsolete. Anyone acquainted with the history of philosophy will know that such is not the case. Logical empiricism is a very simple, not to say simple-minded, philosophy. It is limited in its conception of both logic and empirical knowledge, and on both counts it lacks the apparatus requisite for serving adequately the needs of science, modern and pre-modern alike. But its defects can be remedied by importing elements selectively from the Aristotelian tradition, a tradition in which the philosophy of nature has always played a pivotal role.

42. The methodology he used to do this is described in my *The Role of Demonstration in Moral Theology: A Study of Methodology in St. Thomas Aquinas*. Washington, D.C.: The Thomist Press, 1962.

The logic on which logical empiricism draws most heavily is the formal logic that grew out of attempts to revise the foundations of mathematics. This logic is at its best in constructing axiomatic systems and testing them for consistency and freedom from contradiction. It is a very austere logic, however, and the concepts of truth and certitude it employs are more suited to logic itself and to mathematics than they are to natural science. Science is not an axiomatic system, and not even mathematical physics can be made to fit into the rigidly deductive mold, unless one assumes a "perfect fit" between mathematics and the physical universe and blocks out entirely the imperfections of the real world. Those who proclaim that all science is probable and fallible are under the spell of this view of logic. Truth and certitude it considers from the point of view of logical form, not from that of epistemology. Truth is stark and absolute; either it is present totally or one has its opposite, falsity. No room is allowed for partial truth, or obscure truth, or approximate truth, in the sense in which we have used those expressions. Either one knows everything or one knows nothing. And in the order of nature, that is decidedly not the way humans come to know things. It is possible to grasp a truth in a general way that is subject to further refinement and clarification. Such truth is revisable, but that does not make it fallible. Nor is an approximate truth necessarily probable and thus only a matter of opinion. One can be certain of an approximation, and on that ground the knowledge it provides can be scientific.

The empirical side of logical empiricism presents additional difficulties. One weakness is its professed inability to grasp causal connections, not in Hume's sense of causation, but in the sense of true causal efficacy. Hume associated causality with powers and was unable to grasp them as well. He went along with Descartes in denying the existence of natures and natural or substantial forms. It is true that these are not give directly by the senses, but humans are more than sensing animals; they are also rational animals. There are, again, various degrees of commitment to empiricism. It is one thing to insist that all knowledge begins in sense experience, and quite another to insist that it is impossible ever to transcend the bounds of sense. If one denies to humans the power of intellect and the ability to grasp universals, then obviously science in the epistemic sense becomes impossible. Abstractive induction in the meaning of *epagogē* is essential to the doctrine of the *Posterior Analytics*, but it is at work in all other human knowing as well. It is not the same as the enumerative induction that philosophers of science now commonly associate with the term "induction." Most scientists would not understand the difference between the two. But it is important to note that there is nothing in the training of scientists that requires them to negate their powers of intellect or profess an inability to form a universal or to grasp a causal connection. That is an option taken by some philosophers, but in no way is it requisite for a scientific mentality.

One way of easing the restraints of logical empricism and bringing the philosophy it embodies closer to the ways in which human beings think is to adopt what Arthur Fine has labeled the "Natural Ontological Attitude."[43] In effect, what he proposes is that philosophers of science give scientists the benefit of the doubt. The natural ontological attitude disposes one to accept science as it is. This involves a commitment to take the certified results of science as knowledge claims on a par with the findings of common sense. One can do this without presupposing that all of science is indubitable or that it is incapable of further refinement. Fine's proposal thus fits well with the thesis that has been advanced throughout this chapter. If one equates common sense with reputable opinion, and accords it the status of *endoxa*, to adopt the natural ontological attitude is to grant that most of what scientists hold is true—not in the sense that the content of science in the present day is the last word, but in the minimal sense that it represents a truth that is partial and perhaps obscure, but still able to be completed and clarified in greater detail.[44]

43. In his *The Shaky Game: Einstein, Realism, and the Quantum Theory*, Chicago and London: The University of Chicago Press, 1986, pp. 112–135.

44. Since the notion of common sense is basic to this natural ontological attitude, one may wonder whether Thomas Reid's "philosophy of common sense," though elaborated at the end of the eighteenth century, could have anything to contribute to a modern philosophy of science. In search of an answer to that question, after the manuscript for this book was completed I read Keith Lehrer's revisionist account of Reid's philosophy (*Thomas Reid*, London and New York: Routledge, 1989). As interpreted by Lehrer, Reid's powers are not faculties in a compartmental sense, as they have been frequently understood, but rather information processing systems wherein innate principles serve as programs that deliver universal conceptions and beliefs. Such conceptions are able to validate our internal world of mental operations, as an antidote to eliminative materialism, and also our knowledge of the external world of physical processes, as an antidote to absolute idealism. Surprisingly, Lehrer's analysis illuminates not only the concept of common sense, but also such concepts as causality, realism, intentionality, demonstration, probable reasoning, truth, and certitude, in ways that are remarkably consonant with those explained in previous chapters of this book. His interpretation of Reid's work, directed as the latter is against Hume, will be especially helpful for those who subscribe to a philosophy of science that is basically empirical and yet avoids the extremes of the "old consensus" now being rejected within the movement.

Fine proposes that this attitude be adopted as a core position for philosophers of science who are engaged in the current debate between "realists" and "anti-realists." The debate is ostensibly concerned with the ontological status of theoretical entities. This is a problem whose solution requires a sophisticated understanding of the relationships between real being and logical being, between *ens reale* and *ens rationis*, as this has been explained in Secs. 7.4 and 7.5 above. Unfortunately, participants in the debate, overlooking the nuances to be observed when using these terms, tend to take global positions. For "realists," *all* theoretical entities have existence outside the mind; for "non-realists," *all* are mental constructs. Fine rightfully refuses to take sides in a debate of this kind. In doing so, he clearly accords with the practice of scientists. It would be difficult to find a theoretical physicist who believes that every term in every equation he writes stands for a real entity. Even more difficult would be to find an experimentalist who systematically doubts all of his results and is willing to write them all off as figments of his imagination.

It has been said that philosophy of science is "a subject with a great past," with the implication that the discipline as practiced by logical reconstructionists has run its course and "has nothing whatever to do with what goes on in the sciences."[45] There is obviously truth in the criticism, but that need not entail such a pessimistic view of the philosophy of science. The old consensus is gradually passing away and a new consensus is emerging in the discipline, as noted in Sec. 6.7. One aspect of the old view that is increasingly being called into question is what may be called prescriptive philosophy of science, which was intent on establishing demarcation criteria for separating science from non-science, a euphemism for nonsense or metaphysics. This assumes, as did both Schlick and Popper in the early days of the Vienna Circle, that all of science is in need of interpretation and that such interpretation can be provided only by the philosopher of science. Such a view, which accords to the philosopher a type of understanding superior to that of the scientist, is pretentious, if not arrogant. It is particularly so when one equates philosophy of science with the logic of science, and by "logic" one means modern logic. If, as has been argued in the pages above, truth and certitude in science come from the subject matter, not from logical form, it is the person who is dealing directly with the subject matter, that is, the sci-

45. Paul K. Feyerabend, "Philosophy of Science: A Subject with a Great Past," in *Historical and Philosophical Perspectives of Science*," ed. Roger Stuewer, Minneapolis: Univerity of Minnesota Press, 1970, pp. 172, 181.

entist, who can judge best what his findings mean. The philosopher of science, *qua* philosopher, has no claim to interpretational superiority, and particularly not when philosopher is taken as equivalent to logician. Only to the extent that philosophers happen to be scientists and know their subject matter from within, as it were, are they entitled to speak for the particular discipline.

The position that was advanced in Sec. 6.8 is that philosophy of science is an integral part of the philosophy of nature, and as such is to be distinguished from natural science only in a minimal way. Now, in light of the Aristotelian teaching on *logica utens* and the different ways in which the *Topics* and the *Posterior Analytics* are related to that teaching (Sec. 6.7), along with the specimens of probable argument and demonstration provided in Chaps. 7, 8, and 9, we may elaborate further on that position. The logic with which the philosopher of science in the Aristotelian tradition is concerned is not formal logic but rather the content logic of the *Analytics* and the *Topics*, the former in the case of a demonstration and the latter in the case of a dialectical or probable argument. Only demonstrations, strictly speaking, add to the content of a *scientia*, and the person who discovers a demonstration is a scientist, not a logician in the sense of the *Analytics*. The science whose content was added to by the demonstrations sketched above in Chap. 9 may be regarded as either mathematical physics or natural science, if both of these disciplines are taken in a sufficiently broad sense. Probable arguments, on the other hand, yield *doxa* or opinion, conclusions that are not yet scientific in the sense of being true and certain, and they are the province of the logician in the sense of the *Topics*. They are not definitive enough to add to the content of a science, though they may be seen as pertaining to its subject matter by a sort of dialectical extension.

In the case of demonstrations, there would seem to be a division of labor between the scientist and the qualified philosopher of science on the basis already indicated in Sec. 6.8, namely, that the scientist is doing *in actu exercito* or implicitly what the philosopher is capable of doing *in actu signato* or in a reflective way. This division of labor would have a particularly beneficial application in dispelling the fashionable myth that all science is fallible. The focus here need not be on the frontiers of knowledge, where demonstrations are hard to find, but rather on the past, on the history of science, as in the case histories discussed in the previous chapter and the early parts of the present one. Scientists are continually identifying contributions they implicitly regard as demonstrations or definitive contributions to their subject matter. These become clear in the ways they expand and modify and revise both the textbooks they use to teach the various disciplines and the reference works they use in their own research, such as the *Handbook of Chemisry and Physics*. But scientists are not always intent on clarifying the logic behind the consensus they establish, and thus they leave plenty of room for the philosopher to come to their aid. In this area philosophers of science can surely make worthwhile contributions, those that add to the dignity of science and the respect to be accorded it, rather than to its debunking and devaluation, as does the continued promotion of the fallibility thesis.

In the case of probable arguments, there would seem to be even more room for the philosopher of science to make a positive contribution to the scientific enterprise. Here the philosopher can be seen as someone outside the particular discipline who is capable of arguing on both sides of an issue without necessarily taking a stand—the traditional role of the dialectician. In this role it would be quite proper for a philosopher of science to dispute whether or not all emeralds are green without professing to know anything about the nature of emeralds. Attaching a predicate to the subject would be much like playing a game of roulette, trying to judge what particular predicate is likely to turn up on the basis of previous spins of the wheel, either totally or incrementally considered. Those who seek to apply Bayes's theorem to the problem of induction are pursuing precisely this line of inquiry. In so doing they are not unlike those who attempt to work out norms for judging on the basis of external considerations when a particular theory change is progressive or degenerative, without purporting to know in detail the subject matter with which the theory is concerned. In effect, they are attempting to work out new *topoi* analogous to those employed by Aristotle and others in the peripatetic tradition, as mentioned in the latter part of Sec. 7.8. Both of these types of inquiry generate a substantial literature in the philosophy of science. The fact that much of it may be of little interest to scientists does not deprive it of intrinsic merit. When there is nothing else to go on, extrinsic considerations provide the only remaining resource, a resource to which one can always turn to offer a considered opinion.

There remains a final case for comment, that of probable arguments that are highly confirmed and so constitute what has been referred to as *endoxa* or reputable opinion. This type of argument stands on the borderline between demonstration and probable reasoning, and is best illustrated in the intermediate stage of the demonstrative regress, as this has been described in Sec. 8.6 and repeatedly illustrated in Chap. 9. In a way this would represent the acme of cooperation between the scientist and the competent philosopher of science, for it involves the controversial transition from high probability to certitude. In the early seventeenth century, Galileo and Harvey made that transition by themselves, but then, they were scientists with considerable credentials in traditional logic. In the present day one would hardly expect a scientist to be also a philosopher of science. Yet cooperative ventures between scientists who have strong epistemological interests and philosophers who have competence in scientific matters are now practicable. In such ventures perhaps one would find the ideal complementarity, one uniquely suited to advancing the scientific enterprise.

This hopeful note notwithstanding, one would have to admit that the philosophy of science movement, by and large, has little to contribute to the epistemic dimension of science. In the heyday of the movement, by emulating the mathematician in the use of formal logic and axiomatic method, philosophers of science created an impression of great precision in their analyses. Indeed, for a while they seemed to have achieved a clarity and distinctness in their discourse that would have been the envy of Descartes. But the natures with which they ultimately must deal have continued to be unyielding to their techniques. The approach through the history of science has proved to be more effective, as we have attempted to show, and it has taken us a long way back, very far indeed. Once again "the master of those who know" seems to be beckoning us to reconsider his time-tested methods, with all their difficulties and confusedness, should we still be interested in finding a "secure path" to science.

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