bardo di scienze e lettere, **18** (1898), fasc. 5; and William H. Stahl, "The Greek Heliocentric Theory and Its Abandonment," in *Transactions of the American Philological Association,* **77** (1945), 321–332.

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ARISTOTLE (*b.* Stagira in Chalcidice, 384 B.C.; *d.* Chalcis, 322 B.C.), *the most influential ancient exponent of the methodology and division of sciences; contributed to physics, physical astronomy, meteorology, psychology, biology.* The following article is in four parts: Method, Physics, and Cosmology; Natural History and Zoology; Anatomy and Physiology; Tradition and Influence.

Method, Physics, and Cosmology.

Aristotle's father served as personal physician to Amyntas II of Macedon, grandfather of Alexander the Great. Aristotle's interest in biology and in the use of dissection is sometimes traced to his father's profession, but any suggestion of a rigorous family training in medicine can be discounted. Both parents died while Aristotle was a boy, and his knowledge of human anatomy and physiology remained a notably weak spot in his biology. In 367, about the time of his seventeenth birthday, he came to Athens and became a member of Plato's Academy. Henceforth his career falls naturally into three periods. He remained with the Academy for twenty years. Then, when Plato died in 347, he left the city and stayed away for twelve years: his reason for going may have been professional, a dislike of philosophical tendencies represented in the Academy by Plato's nephew and successor, Speusippus, but more probably it was political, the new anti-Macedonian mood of the city. He returned in 335 when Athens had come under Macedonian rule, and had twelve more years of teaching and research there. This third period ended with the death of his pupil, Alexander the Great (323), and the revival of Macedon's enemies. Aristotle was faced with a charge of impiety and went again into voluntary exile. A few months later he died on his maternal estate in Chalcis.

His middle years away from Athens took him first to a court on the far side of the Aegean whose ruler, Hermeias, became his father-in-law; then (344) to the neighboring island Lesbos, probably at the suggestion of Theophrastus, a native of the island and henceforth a lifelong colleague; finally (342) back to Macedon as tutor of the young prince Alexander. After his return to Athens he lectured chiefly in the grounds of the Lyceum, a Gymnasium already popular with sophists and teachers. The Peripatetic school, as an institution comparable to the Academy, was probably not founded until after his death. But with some distinguished students and associates he collected a natural history museum and a library of maps and manuscripts (including his own essays and lecture notes), and organized a program of research which *inter alia* laid the foundation for all histories of Greek natural philosophy (see Theophrastus), mathematics and astronomy (see Eudemus), and medicine.

Recent discussion of his intellectual development has dwelt on the problem of distributing his works between and within the three periods of his career. But part of the stimulus to this inquiry was the supposed success with which Plato's dialogues had been put in chronological order, and the analogy with Plato is misleading. Everything that Aristotle polished for public reading in Plato's fashion has been lost, save for fragments and later reports. The writings that survive are a collection edited in the first century B.C. (see below, Aristotle: Tradition), allegedly from manuscripts long mislaid: a few items are spurious (among the scientific works *Mechanica, Problemata, De mundo, De plantis*), most are working documents produced in the course of Aristotle's teaching and research; and the notes and essays composing them have been arranged and amended not only by their author but also by his ancient editors and interpreters. Sometimes an editorial title covers a batch of writings on connected topics of which some seem to supersede others (thus *Physics* VII seems an unfinished attempt at the argument for a prime mover which is carried out independently in *Physics* VIII); sometimes the title represents an open file, a text annotated with unabsorbed objections (e.g., the *Topics*) or with later and even post-Aristotelian observations (e.g., the *Historia animalium*). On the other hand it cannot be assumed that inconsistencies are always chronological pointers. In *De caelo* I–II he argues for a fifth element in addition to the traditional four (fire, air, water, earth): unlike them, its natural motion is circular and it forms the divine and unchanging substance of the heavenly bodies. Yet in *De caelo* III–IV, as in the *Physics,* he discusses the elements without seeming to provide for any such fifth body, and these writings are accordingly sometimes thought to be earlier. But on another view of his methods (see below, on dialectic) it becomes more intelligible that he should try different and even discrepant approaches to a topic at the same time.

Such considerations do not make it impossible to reconstruct something of the course of his scientific thinking from the extant writings, together with what is known of his life. For instance it is sometimes said that his distinction between "essence" and "accident," or between defining and nondefining characteristics, must be rooted in the biological studies in which it plays an integral part. But the distinction is explored at greatest length in the *Topics,* a handbook of dialectical debate which dates substantially from his earlier years in the Academy, whereas the inquiries embodied in his biological works seem to come chiefly from his years abroad, since they refer relatively often to the Asiatic coast and Lesbos and seldom to southern Greece. So this piece of conceptual apparatus was not produced by the work in biology. On the contrary, it was modified by that work: when Aristotle tries to reduce the definition of a species to one distinguishing mark (e.g., *Metaphysics* VII 12, VIII 6) he is a dialectician, facing a problem whose ancestry includes Plato's theory of Forms, but when he rejects such definitions in favor of a cluster of differentiae (*De partibus animalium* I 2–3) he writes as a working biologist, armed with a set of questions about breathing and sleeping, movement and nourishment, birth and death.

The starting point in tracing his scientific progress must therefore be his years in the Academy. Indeed without this starting point it is not possible to understand either his pronouncements on scientific theory or, what is more important, the gap between his theory and his practice.

The Mathematical Model. The Academy that Aristotle joined in 367 was distinguished from other Athenian schools by two interests: mathematics (including astronomy and harmonic theory, to the extent that these could be made mathematically respectable), and dialectic, the Socratic examination of the assumptions made in reasoning—including the assumptions of mathematicians and cosmologists. Briefly, Plato regarded the first kind of studies as merely preparatory and ancillary to the second; Aristotle, in the account of scientific and philosophical method that probably dates from his Academic years, reversed the priorities (*Posterior Analytics* I; *Topics* I 1–2). It was the mathematics he encountered that impressed him as providing the model for any well-organized science. The work on axiomatization which was to culminate in Euclid's *Elements* was already far advanced, and for Aristotle the pattern of a science is an axiomatic system in which theorems are validly derived from basic principles, some proprietary to the science ("hypotheses" and "definitions," the second corresponding to Euclid's "definitions"), others having an application in more than one system ("axioms," corresponding to Euclid's "common notions"). The proof-theory which was characteristic of Greek mathematics (as against that of Babylon or Egypt) had developed in the attempt to show why various mathematical formulae worked in practice. Aristotle pitches on this as the chief aim of any science: it must not merely record but explain, and in explaining it must, so far as the special field of inquiry allows, generalize. Thus mathematical proof becomes Aristotle's first paradigm of scientific explanation; by contrast, the dialectic that Plato ranked higher—the logical but free-ranging analysis of the beliefs and usage of "the many and the wise"—is allowed only to help in settling those basic principles of a science that cannot, without regress or circularity, be proved within the science itself. At any rate, this was the theory.

Aristotle duly adapts and enlarges the mathematical model to provide for the physical sciences. Mathematics, he holds, is itself a science (or rather a family of sciences) about the physical world, and not about a Platonic world of transcendent objects; but it abstracts from those characteristics of the world that are the special concern of physics—movement and change, and therewith time and location. So the nature and behavior of physical things will call for more sorts of explanation than mathematics recognizes. Faced with a man, or a tree, or a flame, one can ask what it is made of, its "matter"; what is its essential character or "form"; what external or internal agency produced it; and what the "end" or purpose of it is. The questions make good sense when applied to an artifact such as a statue, and Aristotle often introduces them by this analogy; but he holds that they can be extended to every kind of thing involved in regular natural change. The explanations they produce can be embodied in the formal proofs or even the basic definitions of a science (thus a lunar eclipse can be not merely accounted for, but defined, as the loss of light due to the interposition of the earth, and a biological species can be partly defined in terms of the purpose of some of its organs). Again, the regularities studied by physics may be unlike those of mathematics in an important respect: initially the *Posterior Analytics* depicts a science as deriving necessary conclusions from necessary premises, true in all cases (I ii and iv), but later (I xxx) the science is allowed to deal in generalizations that are true in most cases but not necessarily in all. Aristotle is adapting his model to make room for "a horse has four legs" as well as for "$2 \times 2 = 4$." How he regards the exceptions to such generalizations is not altogether clear. In his discussions of "luck" and "chance" in *Physics* II, and of "accident" elsewhere, he seems to hold that a lucky or chance or accidental event can always, under some description, be subsumed under a generalization expressing some regularity. His introduction to the *Meteorologica* is sometimes cited to show that in his view sublunary happenings are inherently irregular; but he probably means that, while the laws of sublunary physics are commonly (though not always) framed to allow of exceptions, these exceptions are not themselves inexplicable. The matter is complicated by his failure to maintain a sharp distinction between laws that provide a necessary (and even uniquely necessary), and those that provide a sufficient, condition of the situation to be explained.

But in two respects the influence of mathematics on Aristotle's theory of science is radical and unmodified. First, the drive to axiomatize mathematics and its branches was in fact a drive for autonomy: the premises of the science were to determine what questions fell within the mathematician's competence and, no less important, what did not. This consequence Aristotle accepts for every field of knowledge: a section of *Posterior Analytics* I xii is given up to the problem, what questions can be properly put to the practitioner of such-and-such a science; and in I vii, trading on the rule "one science to one genus," he denounces arguments that poach outside their own field—which try, for instance, to deduce geometrical conclusions from arithmetical premises. He recognizes arithmetical proofs in harmonics and geometrical proofs in mechanics, but treats them as exceptions. The same impulse leads him to map all systematic knowledge into its departments—theoretical, practical, and productive—and to divide the first into metaphysics (or, as he once calls it, "theology"), mathematics, and physics, these in turn being marked out in subdivisions.

This picture of the autonomous deductive system has had a large influence on the interpreters of Aristotle's scientific work; yet it plays a small part in his inquiries, just because it is not a model for inquiry at all but for subsequent exposition. This is the second major respect in which it reflects mathematical procedure. In nearly all the surviving productions of Greek mathematics, traces of the workshop have been deliberately removed: proofs are found for theorems that were certainly first reached by other routes. So Aristotle's theoretical picture of a science shows it in its shop window (or what he often calls its "didactic") form; but for the most part his inquiries are not at this stage of the business. This is a piece of good fortune for students of the subject, who have always lamented that no comparable record survives of presystematic research in mathematics proper (Archimedes' public letter to Eratosthenes—the *Ephodos,* or "Method"—is hardly such a record). As it is, Aristotle's model comes nearest to realization in the systematic astronomy of *De caelo* I–II (cf., e.g., I iii, "from what has been said, partly as premises and partly as things proved from these, it follows . . ."), and in the proof of a prime mover in *Physics* VIII. But these constructions are built on the presystematic analyses of *Physics* I–VI, analyses that are expressly undertaken to provide physics with its basic assumptions (cf. I i) and to define its basic concepts, change and time and location, infinity and continuity (III i). *Ex hypothesi* the latter discussions, which from Aristotle's pupils Eudemus and Strato onward have given the chief stimulus to physicists and philosophers of science, cannot be internal to the science whose premises they seek to establish. Their methods and data need not and do not fit the theoretical straitjacket, and in fact they rely heavily on the dialectic that theoretically has no place in the finished science.

Dialectic and "Phenomena." Conventionally Aristotle has been contrasted with Plato as the committed empiricist, anxious to "save the phenomena" by basing his theories on observation of the physical world. First the phenomena, then the theory to explain them: this Baconian formula he recommends not only for physics (and specifically for astronomy and biology) but for ethics and generally for all arts and sciences. But "phenomena," like many of his key terms, is a word with different uses in different contexts. In biology and meteorology the phenomena are commonly observations made by himself or taken from other sources (fishermen, travelers, etc.), and similar observations are evidently presupposed by that part of his astronomy that relies on the schemes of concentric celestial spheres proposed by Eudoxus and Callippus. But in the *Physics* when he expounds the principles of the subject, and in many of the arguments in the *De caelo* and *De generatione et corruptione* by which he settles the nature and interaction of the elements, and turns Eudoxus' elegant abstractions into a cumbrous physical (and theological) construction, the data on which he draws are mostly of another kind. The phenomena he now wants to save—or to give logical reasons (rather than empirical evidence) for scrapping—are the common convictions and common linguistic usage of his contemporaries, supplemented by the views of other thinkers. They are what he always represents as the materials of dialectic.

Thus when Aristotle tries to harden the idea of location for use in science (*Physics* IV 1–5) he sets out from our settled practice of locating a thing by giving its physical surroundings, and in particular from established ways of talking about one thing taking another's place. It is to save these that he treats any location as a container, and defines the place of X as the innermost static boundary of the body surrounding X. His definition turns out to be circular:

moreover it carries the consequence that, since a point cannot lie within a boundary, it cannot strictly have (or be used to mark) a location. Yet we shall see later that his theories commit him to denying this.

Again, when he defines time as that aspect of change that enables it to be counted (*Physics* IV 10–14), what he wants to save and explain are the common ways of *telling* the time. This point, that he is neither inventing a new vocabulary nor assigning new theory-based uses to current words, must be borne in mind when one encounters such expressions as "force" and "average velocity" in versions of his dynamics. The word sometimes translated "force" (*dunamis*) is the common word for the "power" or "ability" of one thing to affect or be affected by another—to move or be moved, but also to heat or to soften or to be heated, and so forth. Aristotle makes it clear that this notion is what he is discussing in three celebrated passages (*Physics* VII 5, VIII 10, *De caelo* I 7) where later critics have discerned laws of proportionality connecting the force applied, the weight moved, and the time required for the force to move the weight a given distance. (Two of the texts do not mention weight at all.) A second term, *ischus,* sometimes rendered "force" in these contexts, is the common word for "strength," and it is this familiar notion that Aristotle is exploiting in the so-called laws of forced motion set out in *Physics* VII 5 and presupposed in VIII 10: he is relying on what a nontechnical audience would at once grant him concerning the comparative strengths of packhorses or (his example) gangs of shiphaulers. He says: let *A* be the strength required to move a weight *B* over a distance *D* in time *T*; then (1) *A* will move 1/2 *B* over 2*D* in *T*; (2) *A* will move 1/2 *B* over *D* in 1/2 *T*; (3) 1/2 *A* will move 1/2 *B* over *D* in *T*; and (4) *A* will move *B* over 1/2 *D* in 1/2 *T*; but (5) it does not follow that *A* will move some multiple of *B* over a proportionate fraction of *D* in *T* or indeed in any time, since it does not follow that *A* will be sufficient to move that multiple of *B* at all. The conjunction of (4) with the initial assumption shows that Aristotle takes the speed of motion in this case to be uniform; so commentators have naturally thought of *A* as a force whose continued application to *B* is just sufficient to overcome the opposing forces of gravity, friction, and the medium. In such circumstances propositions (3) and (4) will yield results equivalent to those of Newtonian dynamics. But then the circumstances described in (1) and (2) should yield not just the doubling of a uniform velocity which Aristotle supposes, but acceleration up to some appropriate terminal velocity. Others have proposed to treat *A* as prefiguring the later idea not of *force* but of *work,* or else *power,* if these are defined in terms of the displacement of weight and not of force; and this has the advantage of leaving Aristotle discussing the case that is central to his dynamics—the carrying out of some finite task in a finite time—without importing the notion of action at an instant which, for reasons we shall see, he rejects. But Aristotle also assumes that, for a given type of agent, *A* is multiplied in direct ratio to the size or quantity of the agent; and to apply this to the work done would be, once more, to overlook the difference between conditions of uniform motion and of acceleration. The fact is that Aristotle is appealing to conventional ways of comparing the strength of haulers and beasts of burden, and for his purposes the acceleration periods involved with these are negligible. What matters is that we measure strength by the ability to perform certain finite tasks before fatigue sets in; hence, when Aristotle adduces these proportionalities in the *Physics,* he does so with a view to showing that the strength required for keeping the sky turning for all time would be immeasurable. Since such celestial revolutions do not in his view have to overcome any such resistance as that of gravity or a medium we are not entitled to read these notions into the formulae quoted. What then is the basis for these proportionalities? He does not quote empirical evidence in their support, and in their generalized form he could not do so; in the *Physics* and again in the *De caelo* he insists that they can be extended to cover "heating and any effect of one body on another," but the Greeks had no thermometer nor indeed any device (apart from the measurement of strings in harmonics) for translating qualitative differences into quantitative measurements. Nor on the other hand does he present them as technical definitions of the concepts they introduce. He simply comments in the *Physics* that the rules of proportion require them to be true (and it may be noticed that he does not frame any of them as a function of more than two variables: the proportion is always a simple relation between two of the terms, the others remaining constant). He depends on this appeal, together with conventional ways of comparing strengths, to give him the steps he needs toward his conclusion about the strength of a prime mover: it is no part of the dialectic of his argument to coin hypotheses that require elaborate discussion in their own right.

It is part of the history of dynamics that, from Aristotle's immediate successors onward, these formulae were taken out of context, debated and refined, and finally jettisoned for an incomparably more exact and powerful set of concepts which owed little to dialectic in Aristotle's sense. That he did not intend his proportionalities for such close scrutiny becomes even clearer when we turn to his so-called laws of natural motion. Aristotle's universe is finite, spherical, and geocentric: outside it there can be no body nor even, therefore, any location or vacuum or time (*De caelo* I 9); within it there can be no vacuum (*Physics* IV 6–9). Natural motion is the unimpeded movement of its elements: centripetal or "downward" in the case of earth (whose place is at the center) and of water (whose place is next to earth), centrifugal or "upward" in the case of fire and (next below fire) air. These are the sublunary elements, capable of changing into each other (*De generatione et corruptione* II) and possessed of "heaviness" or "lightness" according as their natural motion is down or up. Above them all is the element whose existence Aristotle can prove only by a priori argument: ether, the substance of the spheres that carry the heavenly bodies. The natural motions of the first four elements are rectilinear and terminate, unless they are blocked, in the part of the universe that is the element's natural place; the motion of the fifth is circular and cannot be blocked, and it never leaves its natural place. These motions of free fall, free ascent, and free revolution are Aristotle's paradigms of regular movement, against which other motions can be seen as departures due to special agency or to the presence of more than one element in the moving body. On several occasions he sketches some proportional connection between the variables that occur in his analysis of such natural motions; generally he confines himself to rectilinear (i.e., sublunary) movement, as, for example, in *Physics* IV 8, the text that provoked a celebrated exchange between Simplicio and Salviati in Galileo's *Dialoghi.* There he writes: "We see a given weight or body moving faster than another for two reasons: either because of a difference in the medium traversed (e.g., water as against earth, water as against air), or, other things being equal, because of the greater weight or lightness of the moving body." Later he specifies that the proviso "other things being equal" is meant to cover identity of shape. Under the first heading, that of differences in the medium, he remarks that the motion of the medium must be taken into account as well as its density relative to others; but he is content to assume a static medium and propound, as always, a simple proportion in which the moving object's velocity varies inversely with the density of the medium. Two comments are relevant. First, in this as in almost all comparable contexts, the "laws of natural motion" are dispensable from the argument. Here Aristotle uses his proportionality to rebut the possibility of motion in a vacuum: such motion would encounter a medium of nil density and hence would have infinite velocity, which is impossible. But this is only one of several independent arguments for the same conclusion in the context. Next, the argument discounts acceleration (Aristotle does not consider the possibility of a body's speed in a vacuum remaining finite but increasing without limit, let alone that of its increasing to some finite terminal speed); yet he often insists that for the sublunary elements natural motion is always acceleration. (For this reason among others it is irrelevant to read his proportionalities of natural motion as an unwitting anticipation of Stokes's law.) But it was left to his successors during the next thousand years to quarrel over the way in which the ratios he formulated could be used to account for the steady acceleration he required in such natural motion; and where in the passage quoted he writes "we see," it was left to some nameless ancient scientist to make the experiment recorded by Philoponus and later by Galileo, of dropping different weights from the same height and noting that what we see does not answer to Aristotle's claim about their speed of descent. It was, to repeat, no part of the dialectic of his argument to give these proportionalities the rigor of scientific laws or present them as the record of exact observation.

On the other hand the existence of the natural motions themselves is basic to his cosmology. Plato had held that left to themselves, i.e., without divine governance, the four elements (he did not recognize a fifth) would move randomly in any direction: Aristotle denies this on behalf of the inherent regularity of the physical world. He makes the natural motions his "first hypotheses" in the *De caelo* and applies them over and again to the discussion of other problems. (The contrast between his carelessness over the proportionalities and the importance he attaches to the movements is sometimes read as showing that he wants to "eliminate mathematics from physics": but more on this later.)

This leads to a more general point which must be borne in mind in understanding his way of establishing physical theory. When he appeals to common views and usage in such contexts he is applying a favorite maxim, that in the search for explanations we must start from what is familiar or intelligible to us. (Once the science is set up, the deductions will proceed from principles "intelligible in themselves.") The same maxim governs his standard way of introducing concepts by extrapolating from some familiar, unpuzzling situation. Consider his distinction of "matter" and "form" in *Physics* I. He argues that any change implies a passage between two contrary attributes—from one to the other, or somewhere on a spectrum between the two—and that there must be a third thing to make this passage, a substrate which changes but survives the change. The situations to which he appeals are those from which this triadic analysis can be, so to speak, directly read off: a light object turning dark, an unmusical man becoming musical. But then the analysis is extended to cases progressively less amenable: he moves, via the detuning of an instrument and the shaping of a statue, to the birth of plants and animals and generally to the sort of situation that had exercised earlier thinkers—the emergence of a new individual, the apparent coming of something from nothing. (Not the emergence of a new *type:* Aristotle does not believe that new types emerge in nature, although he accepts the appearance of sports within or between existing types. In *Physics* II 8 he rejects a theory of evolution for putting the random occurrence of new types on the same footing with the reproduction of existing species, arguing that a theory that is not based on such regularities is not scientific physics.) *Ex nihilo nihil fit;* and even the emergence of a new individual must involve a substrate, "matter," which passes between two contrary conditions, the "privation" and the "form." But one effect of Aristotle's extrapolation is to force a major conflict between his theories and most contemporary and subsequent physics. In his view, the question "What are the essential attributes of matter?" must go unanswered. There is no general answer, for the distinction between form and matter reappears on many levels: what serves as matter to a higher form may itself be analyzed into form and matter, as a brick which is material for a house can itself be analyzed into a shape and the clay on which the shape is imposed. More important, there is no answer even when the analysis reaches the basic elements—earth, air, fire, and water. For these can be transformed into each other, and since no change can be intelligibly pictured as a mere succession of discrete objects these too must be transformations of some residual subject, but one that now *ex hypothesi* has no permanent qualitative or quantitative determinations in its own right. Thus Aristotle rejects all theories that explain physical change by the rearrangement of some basic stuff or stuffs endowed with fixed characteristics. Atomism in particular he rebuts at length, arguing that movement in a vacuum is impossible (we have seen one argument for this) and that the concept of an extended indivisible body is mathematically indefensible. But although matter is not required to identify itself by any permanent first-order characteristics, it does have important second-order properties. Physics studies the regularities in change, and for a given sort of thing at a given level it is the matter that determines what kinds of change are open to it. In some respects the idea has more in common with the field theory that appears embryonically in the Stoics than with the crude atomism maintained by the Epicureans, but its chief influence was on metaphysics (especially Neoplatonism) rather than on scientific theory. By contrast, the correlative concept of *form,* the universal element in things that allows them to be known and classified and defined, remained powerful in science. Aristotle took it from Plato, but by way of a radical and very early critique of Plato's Ideas; for Aristotle the formal element is inseparable from the things classified, whereas Plato had promoted it to independent existence in a transcendent world contemplated by disembodied souls. For Aristotle the physical world is all; its members with their qualities and quantities and interrelations are the paradigms of reality and there are no disembodied souls.

The device of extrapolating from the familiar is evident again in his account of another of his four types of "cause," or explanation, viz. the "final," or teleological. In *Physics* II 8 he mentions some central examples of purposive activity—housebuilding, doctoring, writing—and then by stages moves on to discerning comparable purposiveness in the behavior of spiders and ants, the growth of roots and leaves, the arrangement of the teeth. Again the process is one of weakening or discarding some of the conditions inherent in the original situations: the idea of purposiveness sheds its connection with those of having a skill and thinking out steps to an end (although Aristotle hopes to have it both ways, by representing natural sports and monsters as *mistakes*). The resultant "immanent teleology" moved his follower Theophrastus to protest at its thinness and facility, but its effectiveness as a heuristic device, particularly in biology, is beyond dispute.

It is worth noting that this tendency of Aristotle's to set out from some familiar situation, or rather from the most familiar and unpuzzling ways of describing such a situation, is something more than the general inclination of scientists to depend on "explanatory paradigms." Such paradigms in later science (e.g., classical mechanics) have commonly been limiting cases not encountered in common observation or discourse; Aristotle's choice of the familiar is a matter of dialectical method, presystematic by contrast with the finished science, but subject to rules of discussion which he was the first to codify. This, and not (as we shall see) any attempt to extrude mathematics from physics, is what separates his extant work in the field from the most characteristic achievements of the last four centuries. It had large consequences for dynamics. In replying to Zeno's paradox of the flying arrow he concedes Zeno's claim that nothing can be said to be moving at an instant, and insists only that it cannot be said to be stationary either. What preoccupies him is the requirement, embedded in common discourse, that any movement must take a certain time to cover a certain distance (and, as a corollary, that any stability must take a certain time but cover no distance); so he discounts even those hints that common discourse might have afforded of the derivative idea of motion, and therefore of velocity, at an instant. He has of course no such notion of a mathematical limit as the analysis of such cases requires, but in any event this notion came later than the recognition of the cases. It is illuminating to contrast the treatment of motion in the *Mechanica,* a work which used to carry Aristotle's name but which must be at least a generation later. There (*Mechanica* 1) circular motion is resolved into two components, one tangential and one centripetal (contrast Aristotle's refusal to assimilate circular and rectilinear movements, notably in *Physics* VII 4). And the remarkable suggestion is made that the proportion between these components need not be maintained for any time at all, since otherwise the motion would be in a straight line. Earlier the idea had been introduced of a point having motion and velocity, an idea that we shall find Aristotle using although his dialectical analysis of movement and location disallows it; here that idea is supplemented by the concept of a point having a given motion or complex of motions at an instant and not for any period, however small. The *Mechanica* is generally agreed to be a constructive development of hints and suggestions in Aristotle's writings; but the methods and purposes evident in his own discussions of motion inhibit him from such novel constructions in dynamics.

It is quite another thing to say, as is often said, that Aristotle wants to debar physics from any substantial use of the abstract proofs and constructions available to him in contemporary mathematics. It is a common fallacy that, whereas Plato had tried to make physics mathematical and quantitative, Aristotle aimed at keeping it qualitative.

Mathematics and Physics. Plato had tried to construct the physical world of two-dimensional and apparently weightless triangles. When Aristotle argues against this in the *De caelo* (III 7) he observes: "The principles of perceptible things must be perceptible, of eternal things eternal, of perishable things perishable: in sum, the principles must be homogeneous with the subject-matter." These words, taken together with his prescriptions for the autonomy of sciences in the *Analytics,* are often quoted to show that any use of mathematical constructions in his physics must be adventitious or presystematic, dispensable from the science proper. The province of physics is the class of natural bodies regarded as having weight (or "lightness," in the case of air and fire), heat, and color and an innate tendency to move in a certain way. But these are properties that mathematics expressly excludes from its purview (*Metaphysics* K 3).

In fact, however, the division of sciences is not so absolute. When Aristotle contrasts mathematics and physics in *Physics* II he remarks that astronomy, which is one of the "more physical of the mathematical sciences," must be part of physics, since it would be absurd to debar the physicist from discussing the geometrical properties of the heavenly bodies. The distinction is that the physicist must, as the mathematician does not, treat these properties as the attributes of physical bodies that they are; i.e., he must be prepared to explain the application of his model. Given this tie-line a good deal of mathematical abstraction is evidently permissible. Aristotle holds that only extended bodies can strictly be said to have a location (i.e., to lie within a static perimeter) or to move, but he is often prepared to discount the extension of bodies. Thus in *Physics* IV 11, where he shows an isomorphic correspondence between continua representing time, motion, and the path traversed by the moving body, he correlates the moving object with points in time and space and for this purpose calls it "a point—or stone, or any such thing." In *Physics* V 4, he similarly argues from the motion of an unextended object, although it is to be noticed that he does not here or anywhere ease the transition from moving bodies to moving points by importing the idea of a center of gravity, which was to play so large a part in Archimedes' *Equilibrium of Planes.* In his meteorology, explaining the shape of halos and rainbows, he treats the luminary as a point source of light. In the biological works he often recurs to the question of the number of points at which a given type of animal moves; these "points" are in fact the major joints, but in *De motu animalium* 1 he makes it clear that he has a geometrical model in mind and is careful to explain what supplementary assumptions are necessary to adapting this model to the actual situation it illustrates. In the cosmology of the *De caelo* he similarly makes use of unextended loci, in contrast to his formal account of any location as a perimeter enclosing a volume. Like Archimedes a century later, he represents the center of the universe as a point when he proves that the surface of water is spherical, and again when he argues that earth moves so as to make its own (geometrical) center ultimately coincide with that of the universe. His attempt in *De caelo* IV 3 to interpret this in terms of perimeter locations is correct by his own principles, but confused.

This readiness to import abstract mathematical arguments and constructions into his account of the physical world is one side of the coin whose other face is his insistence that any mathematics must be directly applicable to the world. Thus, after arguing (partly on dialectical grounds, partly from his hypothesis of natural movements and natural places) that the universe must be finite in size, he adds that this does not put the mathematicians out of business, since they do not need or use the notion of a line infinite in extension: what they require is only the possibility of producing a line *n* in any required ratio with a given line *m*, and however large the ratio *n/m* it can always be physically exemplified for a suitable interpretation of *m*. The explanation holds good for such lemmata as that applied in Eudoxus' method of exhaustion, but not of some proportionalities he himself adduces earlier in the same context or in *De caelo* I. (These proportionalities are indeed used in, but they are not the subject of, *reductio ad absurdum* arguments. In the *De caelo* Aristotle even assumes that an infinite rotating body would contain a point at an infinite distance from its center and consequently moving at infinite speed.) The same concern to make mathematics applicable to the physical world without postulating an actual infinite is evident in his treatment of the sequence of natural numbers. The infinity characteristic of the sequence, and generally of any countable series whose members can be correlated with the series of numbers, consists just in the possibility of specifying a successor to any member of the sequence: "the infinite is that of which, as it is counted or measured off, it is always possible to take some part outside that already taken." This is true not only of the number series but of the parts produced by dividing any magnitude in a constant ratio; and since all physical bodies are in principle so divisible, the number series is assured of a physical application without requiring the existence at any time of an actually infinite set of objects: all that is required is the possibility of following any division with a subdivision.

This positivistic approach is often evident in Aristotle's work (e.g., in his analysis of the location of *A* as the inner static boundary of the body surrounding *A*), and it is closely connected with his method of building explanations on the familiar case. But here too Aristotle moves beyond the familiar case when he argues that infinite divisibility is characteristic of bodies below the level of observation. His defense and exploration of such divisibility, as a defining characteristic of bodies and times and motions, is found in *Physics* VI, a book often saluted as his most original contribution to the analysis of the continuum. Yet it is worth noticing that in this book as in its two predecessors Aristotle's problems and the ideas he applies to their solution are over and again taken, with improvements, from the second part of Plato's *Parmenides.* The discussion is in that tradition of logical debate which Aristotle, like Plato, called "dialectic," and its problems are not those of accommodating theories to experimentally established facts (or vice versa) but logical puzzles generated by common discourse and conviction. (But then Aristotle thinks of common discourse and conviction as a repository of human experience.) So the argument illustrates Aristotle's anti-Platonic thesis that mathematics—represented again in this case by simple proportion theory—has standing as a science only to the extent that it can be directly applied to the description of physical phenomena. But the argument is no more framed as an advance in the mathematical theory itself than as a contribution to the observational data of physics.

Probably the best-known instance of an essentially mathematical construction incorporated into Aristotle's physics is the astronomical theory due to Eudoxus and improved by Callippus. In this theory the apparent motion of the "fixed stars" is represented by the rotation of one sphere about its diameter, while those of the sun, moon, and the five known planets are represented each by a different nest of concentric spheres. In such a nest the first sphere carries round a second whose poles are located on the first but with an axis inclined to that of the first; this second, rotating in turn about its poles, carries a third similarly connected to it, and so on in some cases to a fourth or (in Callippus' version) a fifth, the apparent motion of the heavenly body being the resultant motion of a point on the equator of the last sphere. To this set of abstract models, itself one of the five or six major advances in science, Aristotle makes additions of which the most important is the attempt to unify the separate nests of spheres into one connected physical system. To this end he intercalates reagent spheres designed to insulate the movement of each celestial body from the complex of motions propelling the body next above it. The only motion left uncanceled in this downward transmission is the rotation of the star sphere. It is generally agreed that Aristotle in *Metaphysics* XII 8 miscalculates the resulting number of agent and reagent spheres: he concludes that we need either fifty-five or forty-seven, the difference apparently representing one disagreement between the theories of Eudoxus and Callippus, but on the latest computation (that of Hanson) the figures should be sixty-six and forty-nine. The mistake had no effect on the progress of astronomy: within a century astronomers had turned to a theory involving epicycles, and Aristotle's physical structure of concentric nonoverlapping spheres was superseded. On the other hand his basic picture of the geocentric universe and its elements, once freed from the special constructions he borrowed and adapted from Eudoxus, retained its authority and can be seen again in the introductory chapters of Ptolemy's *Syntaxis.*

Conclusion. These arguments and theories in what came to be called the exact sciences are drawn principally from the *Posterior Analytics, Topics, Physics, De caelo* and *De generatione,* works that are generally accepted as early and of which the first four at least probably date substantially from Aristotle's years in the Academy or soon after. The influence of the Academy is strong on them. They are marked by a large respect for mathematics and particularly for the techniques and effects of axiomatizing that subject, but they do not pretend to any mathematical discoveries, and in this they are close in spirit to Plato's writings. Even the preoccupation with physical change, its varieties and regularities and causes, and the use of dialectic in analyzing these, is a position to which Plato had been approaching in his later years. Aristotle the meticulous empiricist, amassing biological data or compiling the constitutions of 158 Greek states, is not yet in evidence. In these works the analyses neither start from nor are closely controlled by fresh inspections of the physical world. Nor is he liable to think his analyses endangered by such inspections: if his account of motion shows that any "forced" or "unnatural" movement requires an agent of motion in constant touch with the moving body, the movement of a projectile can be explained by inventing a set of unseen agents to fill the gap—successive stages of the medium itself, supposed to be capable of transmitting movement even after the initial agency has ceased acting. In all the illustrative examples cited in these works there is nothing comparable to even the half-controlled experiments in atomistic physics and harmonics of the following centuries. His main concerns were the methodology of the sciences, which he was the first to separate adequately on grounds of field and method; and the meticulous derivation of the technical equipment of these sciences from the common language and assumptions of men about the world they live in. His influence on science stemmed from an incomparable cleverness and sensitiveness to counterarguments, rather than from any breakthrough comparable to those of Eudoxus or Archimedes.

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ARISTOTLE: Natural History and Zoology.

It is not clear when Aristotle wrote his zoology, or how much of his natural history was his own work. This is unfortunate, for it might help us to interpret his philosophy if we knew whether he began theorizing in biology before or after his main philosophical formulations, and how many zoological specimens he himself collected and identified. Some believe that he began in youth, and that his theory of potentiality was directed originally at the problem of growth. Others (especially Jaeger) hold that his interest in factual research came late in life and that he turned to biology after founding the Lyceum. Most probably, however, it was in middle life, in the years 344–342 B.C., when he was living on Lesbos with Theophrastus; many of his data are reported from places in that area. This would imply that he wrote the zoology with his philosophical framework already established, and on the whole the internal evidence of the treatises bears this out. It follows that in order to understand his zoological theory, we must keep his philosophy in mind. Yet it may also be true that in thinking out his philosophy, he was conscious of biological problems in a general way.