3 **Rapid #: -4873358** 4 **Ariel IP: 150.135.238.50**

Status	Rapid Code	Branch Name	Start Date
Pending	BOS	Main Library	10/25/2011 3:09:06 PM

CALL #:	**B21 .F61**
LOCATION:	**BOS :: Main Library :: Mugar Library**
TYPE:	Article CC:CCL
JOURNAL TITLE:	Studies in philosophy and the history of philosophy
USER JOURNAL TITLE:	Studies in philosophy and the history of philosophy
BOS CATALOG TITLE:	Studies in philosophy and the history of philosophy
ARTICLE TITLE:	Duhem's Interpretation of Aristotle on Mathematics in Science
ARTICLE AUTHOR:	Francis J. Collingwood
VOLUME:	22
ISSUE:	
MONTH:	
YEAR:	1991
PAGES:	unknown 63-79
ISSN:	0585-6965
OCLC #:	1766739
CROSS REFERENCE ID:	[TN:996513][ODYSSEY:150.135.238.6/ILL]
VERIFIED:	

BORROWER:	**AZU :: Main Library**
PATRON:	**Alan G Aversa**
PATRON ID:	aversa
PATRON ADDRESS:	
PATRON PHONE:	
PATRON FAX:	
PATRON E-MAIL:	
PATRON DEPT:	
PATRON STATUS:	
PATRON NOTES:	

RAPID

System Date/Time: 10/26/2011 7:33:46 AM MST

AN 10/26/11

5 Duhem's Interpretation of Aristotle on Mathematics in Science

FRANCIS J. COLLINGWOOD

Science goes on as the curiosity of man sends him observing and cataloguing in myriad fields. Each new day and week sees more revelations as the incredibly sophisticated worlds of things and their activities yield to experiment and thought. Attempts to say what it all means and to understand how all the sorts of fields, and atomic and subatomic particles, co-relate, pass for philosophies of science. Said philosophies are concerned with methodology as well as with content. Each such philosophy tends to mirror the development of the physical sciences at the time of its writing. I wish to call attention to a philosophy of physics written by Pierre Duhem, who had the double qualification of being not only an excellent teacher and contributor to the field of thermodynamics but also a very accomplished historian of science. The first qualification means that he was well acquainted with the field he analyzed and conversant with allied sciences; the second means that he knew of a great number of historical attempts to develop physics and astronomy, with the varying degrees of success achieved. Thus his theory about the purpose and the proper procedures of physical science represents the best that one could expect to find at the turn of the last century. I believe that it well illustrates the thesis that there are perennial aspects to physical philosophy; that in seeking to make the world of inanimate matter intelligible, man continues to do the same sort of thing. He attempts to make new discoveries become a continuation of current beliefs. He attempts to make the world intelligible by quantifying the data that research turns up and by stating the laws of nature. In this way he systematizes his apprehensions of nature so as to understand it better. The explicit part of the systematizing of experience is of ancient origin. However, it has changed little in its aim of setting up clear-cut classifications of things and of making reductive explanations of complex things in terms of their components. Concentrating on the results of this activity is elaborating a theory about how nature works; it is making a philosophy of nature.

The first philosophy of nature that attempted to go beyond mere claims and untestable hypotheses was elaborated by Aristotle. It provided several very valuable notions in the attempt to understand material reality. It is found in the second book of his *Physics* as presuppositions about the role of causes in events and as a belief in the orderly repetitive sequencing of natural processes. There are other analyses of nature in other places in his writings, but nowhere is his philosophy of nature completely elaborated as a single coherent system. Aristotle also set down some fundamental truths about an empirical approach to constructing physical science. These also have to be gathered from various works. Duhem's writings show that he was quite conversant with this theory about doing science for he incorporated most of it into his attempt to explain what science is all about. However, Aristotle was a better theorist than he was a practitioner. His own attempts to investigate physical problems led him into unjustified assumptions and erroneous conclusions. Unfortunately for the progress of science and mankind, he had many followers in the succeeding centuries who followed his erroneous science and neglected his excellent methodology, which insisted upon the need to rely on actual experience as the warrant for doing science. Duhem gave a somewhat elaborate version of Aristotle's philosophy of science while he was developing what might be called a philosophy of scientific methodology. Thus Aristotle's philosophy of nature, as the presuppositions that underlie all physical science, as well as his theory of empirical knowing, is in Duhem's philosophy of science.

Duhem is noteworthy for both the rigor of his thinking and the clarity of his ideas as a physicist in the forefront of his field. He should have had a professorship in Paris, but pettiness forbade this.[1] He wrote with such conviction and expertise about the nature of physical science that it seems worthwhile to me to see how enduring is his analysis in a world that has seen so many revolutionary discoveries in physics and astronomy since his death in 1916. It is because I see a continuous thread of theory running from the pre-Socratics through Plato and Aristotle and Duhem (among others) into the present scientific enterprises that I brashly call this enduring viewpoint of science a perennial one. In what follows, I will elaborate, on my own, implications and

1. Stanley L. Jaki, *Uneasy Genius: The Life and Work of Pierre Duhem* (Boston: Martinus Nijhoff Publishers, 1984). In this work Jaki gives a heavily documented account of Duhem's life and of all his writings. See pp. 27–53 for the vengeance executed against Duhem by a prestigious author in the field of thermodynamics whose prized hypothesis was totally discredited in Duhem's doctoral dissertation.

consequences of Aristotle's well-known teachings, in order to give a fuller presentation of his philosophy, which he often stated so concisely. I do this in order to round out the fine Aristotelian influence that made Duhem's account of how to proceed in science so good.

The material causes that have preoccupied much of physical speculation and research have changed in kind from time to time and are still far from certain. However, that there is a reality underlying appearances is a perennial belief. Parmenides and Democritus, each in his own way, discounted the credibility of man's senses in reporting about our physical surrounds. Plato too saw sensation as fallacious. In a striking declaration, in the beginning of the *Timaeus*, he holds that any account of the physical universe will be a mere saving of the appearances of things by resorting to probabilities. Aristotle also believed that things may have parts that are qualitatively different from the composite whole. These are substrates underlying appearances. But he parts company with his predecessors on the issue of the reliability of the senses in reporting the appearance of physical substances. He holds that man's only access to the realm of nature lies in the ability of our external senses to replicate the appearances of things in our sensory consciousness. The sense in act becomes the sensible in act.[2] Rephrased, what we sense is the appearances of physical things: that is, things are for the senses what they appear to be. If there were some way of getting at the appearances of things other than by sensing, a check on them could be carried out. Certainly, in Aristotle's time, no such alternative knower existed. Consequently, then, as now, we must depend upon our senses, and the instruments that extend them, for the facts of nature. The human direct senses are usually fairly reliable for they cannot be made to detect what is not there, by imagination, or by intellect, or by memory, without our deliberately intending to do so. Apart from defects in the sensory organ, which might lead to a false identification of what is present, Aristotle saw no impediment to the senses acting naturally and detecting the colors, sounds, tastes, and so on, that are given in sensation. Viewpoints may obtrude, so that we have a bias when we are observing, as in wanting to see circular motion in a planetary revolution. This sort of false seeing would be an error of judgment in Aristotle's way of analyzing consciousness. By contrast, the sense, identifying with the quality of the sensible present to it, is specified by the actual determinate aspects of the sensible and thus obtains a reliable replica of how the quality exists in fact.

Aristotle repeatedly stated his theory that our senses have as their

2. *De Anima*, III, 2, 425b, 25.

proper function the correct reporting of the appearances of things, qua sensed. The sensed sensible has only an introspective existence. No one has successfully located one nor given a physical description of one; nor has any aspect of memory or imagination, or their contents, been successfully described physically or physiologically to date. As the sensed appearance of things it exists only in sensory consciousness. In short, introspective awareness is the first step in science, for it alone replicates for us, in our consciousness where we can work with it, that which exists in nature. So our being able to speak of sense data with a fair amount of agreement, even though no one has ever experienced one objectively, so as to describe it or to measure it, implies a uniformity of human sensation to that degree. What can be located in the public realm is the physical thing itself and the language or other signs referring to it. What the sense is receiving, or has received, from physical sources is privy to the sentient being that is conscious of it. Consequently, since no generalization as such, nor any science as such, nor any other sort of explanation as such is given in nature, all of these will be the result of human activity. Man in doing science will always be doing the same thing: using his perceived sense data in making up classifications, looking for the underlying factors and the encompassing principles, and trying to capture the whole of reality in his language or other conventional device. This is how he makes matter intelligible to himself.

Because neither language nor any other purely conventional device can replicate the actual features of matter, there will be a lack of fit between the thing under investigation and its description: words are abstract; things are infinitely detailed. The indispensable generalizations, which enable us to encompass all gravitational phenomena, as being attraction of mass for mass, for example, are incurably abstract. So are the common nouns that we use to typify things and to describe them. Both are instruments of understanding, and neither replicates things for any faculty, including understanding. This sort of reading of what is in nature is not at all the same as the feature by feature, detail by detail replication of physical things by a sense. However, they are complementary in human cognition as a whole. The dichotomy between what is sensed and how it is understood is a reason for Aristotle's concluding that mind cannot be classed as one of the human senses. "Most of all the senses make us know and bring to light many differences between things . . . we do not regard any of the senses as wisdom; yet surely these give the most authoritative knowledge of particulars."[3]

3. *Metaphysics* I, 1, 980a, 27, and 981b, 10.

In my view, this dichotomy is also a reason for relying on quantitative analysis of data to construct science. Quantity, as a component of every physical thing, can be known with an ever-increasing accuracy that approaches the exactness of stated physical laws. I will complete my brief review of what Aristotle held, at least implicitly, and that Duhem held explicitly. Science begins with careful observations. It is constructed in the human mind and is often tested for its value on the observational level. After looking at things through the senses the mind turns to its own devices, such as definitions, causal dependencies, other relationships, compositions, and geneses, and so on. With these it works out a theory about what appears to exist and what appears to be going on. Then it refers to the real world to determine whether it has saved the appearances. Science is a mental artifact that enables us to understand reality as it appears and to manipulate it. It enables us to predict some futures with reasonable accuracy in terms of what most probably will occur. All this is done with conventional nonreplicating symbols. Only our senses, with sometimes the aid of instruments, put us in actual contact with matter in a cognitive manner. More often today, as Duhem points out, our senses enter into science only to read the findings of the instruments, a sensory effort totally directed by and meaningful only to the mind.[4]

Aristotle relied on the endless repetitions of appearances to assure himself that although change is a constant occurrence in nature, nevertheless there are repeated similarities there also. Thus regularly any olive seed that sprouted begat an olive seedling, which grew to maturity and yielded a harvest of olives. The constant continuation of living species through reproduction manifested both regularity and causal dependence as reliable bases for correct prediction of events in the realm of appearances. I like to call this assurance of the connectedness of things the uniformity of nature. It is a main plank in Aristotle's philosophy of nature. He argues for it in *Physics* II as a generalization based upon observations open to anyone. It is a powerful belief supporting the elaboration of universals based upon repetitions. It supports the whole of astronomy and of particle physics, which constantly extrapolate, from a limited range of experience, to infer that similar or identical properties exist beyond the range of hands-on testing.

For Aristotle, the discerning of often repeated dependencies triggered the grasping of the dependency relationship by astute observers. Thus that a certain treatment always cures a certain kind of fever

4. Pierre Duhem, *The Aim and Structure of Physical Theory*, trans. Philip P. Wiener (Princeton, N.J.: Princeton University Press, 1954), pt. 2, chap. 4.

gives the medical person assurance of what to prescribe.[5] The need to have seed for the propagation of animal and vegetative life confirms the relationship of these two in the mind of the man of science. Repetition is characteristic of nature. The reassurance engendered by repetition of the same experiences led to an understanding that could be verbalized in a general way. According to Aristotle, just as the essential characteristics of a human being are manifested in the appearances and activities of each one, and so of any one, so also in more complex matters each instance will be typical. As he put it, the universal is present in the particular, although the mind may fail to see it.[6] Presumably we need many similar experiences, and these are the particulars, in order to attract our attention. But as far as his theory goes any one olive will have whatever it takes to be an olive and so will have the essence of olive and be a suitable locus for intuiting the universal. For the fabulous E. Rutherford a few instances of alpha particles' being repelled straight back to their source of emission led to the intuition that the atom had a positively charged very tiny nucleus, which reversed the positively charged alphas in their tracks. In mathematical matters one may intuit the essence of a straight line, or of a sphere, in the first experience of them but be lacking the proper language to express what seems so obvious. When these intuitions are stated as axioms, and understood, there seems to be a uniformity of mind that binds most persons to assent to the axioms. But this clarity is never found in physics.[7]

Outside the realms of mathematics and of commonsense awareness of things, the discovery and positing of general truths of nature require concentration to find the regularly recurring causal dependencies. Quite often this involves many people working on the same task, and experimental tampering with nature as well. Duhem was well aware of this. He wrote brilliant reports of his own research, giving credit to everyone who in any way assisted in his progress. He also made painstaking studies of the onset and development of particular notions in astronomy and chemistry and physics. He believed in the gradual progression of budding hypotheses into confirmed laws. There are no self-evident truths springing from the tedious labor of research. But it is all worthwhile, and sometimes the result of the calculating and pondering will be some quite fruitful generalization about the facts. Consider, for example, the mind-shattering results of

5. *Metaphysics* I, 981a, 5.
6. *The Posterior Analytics*, II, 19, 100a, 5.
7. Duhem dwells on this point, that physics is laborious and fraught with difficulties that are not found in mathematics. Cf. Duhem, *Aim*, II, 7.

research into blackbody radiation. An iron rod heated to a high temperature emits various colors of light, but no satisfactory formula expressed this correctly until Max Planck thought of treating the energy involved as if it existed in small chunks, even though the light was thought of as being waves. This is expressed in the abstract formula $E = h\nu$. This is read, the energy of a wave or particle is the product of its frequency multiplied by Planck's constant h. This formula signaled the start of quantum physics. It related the energy of a particle to frequencies, which differ from one another by definite discrete intervals. A whole host of phenomena related to the wave interpretation of radiated energy are adequately expressed in this formula. This is an example of the economy of thought that Duhem saw as the primary aim of physical theory. Had Duhem adopted this new way of doing energetics, as his way of developing thermodynamics was called, no doubt his brilliant mind would have contributed greatly to the advances in physics and chemistry that followed Planck's breakthrough. But Duhem was abiding by what he took to be the most prudent way to proceed in science, by refusing to grant status to tenuous hypotheses before they received solid evidence in their favor.

Since Aristotle's time experience has taught us to beware of taking anomalous instances as completely typical of olives or whatever. We have also learned that although general propositions often contain a valuable point of view, they may lead us to think that we know what we do not know. Aristotle's own error, in limiting his version of gravitational attraction to the center of the earth, proved to be a stumbling block to his followers for centuries. Nevertheless, in a realist approach to science, it is necessary to take observations into account in order to declare a general proposition.

General propositions are the basis of that part of Aristotle's logic that seeks to use demonstration as a method of drawing out implications. For example, man's being rational implies that he can laugh at the silly irrational experiences he may have. Rationality is the middle term, linking "being human" and "being able to laugh." Demonstrations do not abound in the Aristotelian writings. Middle terms were not easy to find in complex matters. However, the use of mathematics in the development of scientific knowledge was known to him. In his analysis of sensory apprehension Aristotle noted that the properties of size and shape, and of being in motion or at rest, are true of every physical object. Although, according to Aristotle, the quantitative and qualitative aspects of matter are inseparable, in reality they are separable in consciousness. Quantity can be considered in itself, as spatial displacement, without any mention of the qualitative aspects of things.

Of course, the qualities do locate the quantities for our senses in actual experience. However, since every visible object is a quantity, that fact is a basis for an analysis of the quantitative aspects of all bodies. Even though our judgments can be deceived in these matters, Aristotle aimed his study of physics at spatial magnitudes and motion and time. Mathematics, a science of quantity in its own right, would be an excellent instrument to assist in this endeavor. Thus he described optics and astronomy as physical branches of mathematics. He depicted them as studying mathematical lines qua physical: that is, treating physical lines as approximations to the purely ideal mathematical lines, which have extension in one direction only.

It was the investigation of such almost perfectly straight lines of sunlight, casting perfectly even-edged shadows, that played a role in Newton's belief that light was a stream of corpuscles. Light waves would, he thought, bend and show a ragged edge. Closer analysis would have shown diffraction of the light at the edges and challenged the corpuscular theory. The claims that light is a wave and that light is a particle were being put forth in Duhem's science of energetics, and he said that there is no crucial experiment that can decide the issue. Since light has never been made to show its face, the hypotheses involved are unevidenced. Consequently any hypothesis that saves the appearances is not preferable to any other similarly successful hypothesis. They are equally simply learned guesses. Today we must accept that light acts like a wave at times and also acts at times like particles, photons.

Scientific knowledge is attained when we become acquainted with the principles, conditions, and simplest elements of the objects of inquiry; such is the stipulation in the opening lines of *Physics* I. There follows a theory about the underlying substrates of physical things. In *Physics* II nature as the domain of self-perfecting activities of living things is discussed. It is in this book that the basic principles of Aristotle's philosophy of nature are to be found. The actual study of living things, other than man, is found in the biological writings. That is perhaps why the second book of the *Physics* only sets down the causes of physical things and the principles of analysis of nature as goal-oriented and contains no further discussion of living things.

The science of nature is concerned with spatial magnitudes and motion and time, we are told in the beginning of *Physics* III. It is in the subsequent part of this book that the problematic that was the chief interest of Aristotelian cosmologists is to be found. But also it is here that Aristotle departs from his stated best procedure for obtaining true science. He indulges in speculation based on insufficient observation and in some cases on no empirical information at all. His followers took this tack, ignoring, as he did, his own excellent analysis of how to proceed in setting up physical science. This must have scandalized Duhem, for, in his own theory of science, he insists on sticking to the methods that are aimed at preventing the intrusion of any unjustified principles and of any unevidenced claims. As a historian of science Duhem thoroughly analyzed the physical doctrines of many of his predecessors in science. His *Le Système du Monde* is a ten-volume history of cosmological research covering the period from Plato to Copernicus. In it Duhem saw a turning point in the direction that cosmological speculation was taking with the condemnation of errors in the teachings of the Aristotelians, by the bishop of Paris, Etienne Tempier, in 1277. At stake was the belief in the unlimited power of the Christian God conflicting with the interpretations about motion and place and infinity, and so on, that Aristotle had discussed in *Physics* III.

> From the start of the fourteenth century the grandiose edifice of peripatetic physics was doomed to destruction. Christian faith had undermined all its essential principles . . . astronomy had rejected its consequences. The ancient monument was about to disappear; modern science was about to replace it.[8]

This terse statement is accompanied by a scolding of those who had claimed that the medieval period was barren of meaningful discussions of science. Duhem shows beyond dispute that the period was alive with speculation and controversy. The ten volumes are witness to how widespread was the interest in science in the medieval universities. Another text is more explicit on the clash between Christian belief and Aristotelian science.

> But Christian orthodoxy grew angry with the numerous fetters Peripatetic philosophy and Averroism imposed in the name of logic upon divine omnipotence; it decided to break the fetters. In 1277, at the request of Pope John I, Etienne Tempier, bishop of Paris, convened an assembly of doctors of the Sorbonne, and other wise men. Without exception these theologians condemned every proposition that refused God the power to accomplish an act, under the pretext that the act was in contradiction with the Physics of Aristotle and Averroes. . . . In any case, even those who contested the validity of the condemnation did not dare uphold that the Assembly of 1277 formulated something nonsensical; they were constrained to admit, in contradiction to Aristotle's opinion, that one can attribute a movement to the universe as a whole without speaking words that signify nothing.[9]

8. Pierre Duhem, *Medieval Cosmology: Theories of Infinity, Place, Time, Void, and the Plurality of Worlds*, ed. and trans. Roger Ariew (Chicago and London: University of Chicago Press, 1985), paperback 1987. This is an abridged English translation of *Le Système du Monde*. Cf. p. 3.

9. Op. cit., 180.

Duhem saw Christian doctrine about the omnipotence of God as the factor that liberated medieval speculators from the errors of Aristotle. But it did not liberate them from relying on introspection. It did not reawaken in them the Stagirite's analysis of the direct senses as the only reliable testers of scientific claims. That liberation was long in coming.

What he saw in medieval science undoubtedly made Duhem aware of the sterility of speculation without recourse to actual experience of the physical world. It is with the qualities and the quantities that our senses make present to us that we are to begin our investigations of physical phenomena. Also the reduction to absurdity, a logical procedure, so favored by the medieval scholar, must be replaced by a mathematics that enables the physicist to calculate results. The aim of investigation remains the same as Aristotle had said. We need general propositions, based on repeated experiences of regularly recurring events, which enable us to understand those experiences in one sure intelligible grasp. What can be accomplished then is the achieving of the desired economy of thought, as the multiple, with its vagaries, gives way to the essential, as stated by the mind.

Duhem, because of his adherence to safe procedures, has been singled out for criticism as being opposed to progress in science.[10] I will elaborate upon my version of what Aristotle was claiming, as a basis for defending Duhem against that charge. When I take Aristotle literally, he says that the transition from sensory experience to the universal is a sort of induction and that the universal is a generalization based upon repeated experiences of a connection between events. What I take to be essential here is the relation between the events that are named as parts of the general proposition. The relatedness is given in sensory experience; the mind declares the relation. There are irregularities in the appearances, but these will not deter the physicist, for experience has taught him how to read the data. That the relation holds in all instances that have been experienced is the basis for proclaiming a physical law. One may be so sure of the truth of the generalization that he believes that he sees the necessity of the relation, that things could not be otherwise. But nothing in experience has given any reason to claim a knowledge about substrates underlying the bases for the proclaimed law. Whoever wants to introduce such factors must draw them from imagination and endow them with physical properties. For Duhem this is a waste of time, in trying to explain

10. Duhem, *Aim.* The foreword, written by de Broglie, criticizes Duhem for his antipathy to pictorial models.

what is fairly evident by what is obscure. Thus today's talk about gravitons, as the carriers of the gravitational force, would be interesting speculation; searching for them, without a clue as to their reality, would appear to be a poor use of time. It would be abandoning the empirical approach in order to chase chimeras.

Duhem was slow to embrace some new theories. His Aristotelianism led him to make the obtaining, and collating, of general propositions a paramount goal of scientific thinking. Duhem reasoned along this line of thought that the finer features of the objects being correlated by the law are not immediately relevant to the statement of the law, nor to its use. Similarly, what might be theorized about the smaller parts of the objects being analyzed, or about hidden processes, and the like, is not relevant as far as the statement of the law is concerned. Only when the smaller parts can be clearly discerned and the hidden processes brought to light can the lawlike behavior and predictable consequences be declared assuredly. However, prior to this, any guess that saves the appearances presents a mere possibility; no established law of physics need give way to this.

Duhem had great scorn for the controversies in which the learned medieval Aristotelians had engaged. They had departed from Aristotle's theory of science with its stress on experience. This was bad Aristotelianism! Only in the abandoning of eccentrics and epicycles in astronomy and in the destruction of Aristotle's dynamics with the creation of a new one did they appeal to observation. The attack by Tempier on Aristotelianism resulted not in a wholesale return to observation and discovery but rather to exploration of new possibilities in thought. That the new tack in thinking and discussing bore its own kind of fruit is evidenced by the invention of the infinitesimal calculus. Duhem tells us this in *Le Système du Monde*,[11] and he also makes clear that it is not discussion, nor novelty, that he deplores. It is the pursuit of Aristotle's sallies into the realm of conjecture, his fallible opinions about invisible factors, such as the longing by the elements to be in their natural place, that he finds deplorable. In his own chosen field he encountered the same sorts of discussion, the same bad Aristotelianism, and proclaimed their irrelevance to the task of understanding physical reality. In his faithfulness to the notion of logically deducing conclusions implicit in general propositions, he refuses to guess at, or otherwise to invent, underlying causes.[12] Thus he was cool to the theories about nuclei and electrons; they are invisible and unfamiliar,

11. Duhem, *Medieval Cosmology*, 4.
12. Duhem, *Aim*, pt. 2, chap. 1.

and they are built from guesses that border on the bizarre. Such theories were about factors outside the realm of repeatable experience for all but the very few. Also they were not related to observable facts until Niels Bohr presented his theory, which coincided with facts of spectrometry. Be it noted that Planck was hesitant to accept the hypothesis of molecules and atoms at first. Also Einstein, who put forth the theory of the photon, a particle, to complement the wave theory of light, might well be said to have resisted progress in rejecting the indeterminacy principle because he would not relinquish his belief in a rationally ordered universe.

Louis de Broglie chided Duhem for his reluctance to accept new factors being proposed in the field of thermodynamics, such as the electron. Yet de Broglie himself had to overcome his reluctance in introducing the theory of the wavicle. This involved the belief that an electron has the properties of both a wave and a particle, an apparent self-contradiction.[13]

Duhem merely showed the wise reticence, also practiced by other great minds, in wanting to be sure of the reality of his theorizing. De Broglie felt that he had to overcome the failure of experiment to determine that light is a wave and not a particle. This was a giant step forward for science, in which many brilliant scientists cooperated. However, it increased the gap between the visualizable and the intelligible. The existence of such a gap is of major importance in Duhem's philosophy of science. In retrospect, it appears that both Duhem and de Broglie were right even though different in their approaches. Duhem's faithfulness to deduction from general propositions would surely have brought him to see the validity of some of the conclusions about microparticles and fields had he lived longer in the era when these explanatory factors were slowly gaining currency. Securing progress in physics is often very, very difficult. That Duhem should be unwilling to dabble in what he felt were unfounded conjectures is not surprising in view of his experiences in researching the ancient and medieval cosmologists.

I have maintained that Duhem was influenced by two sorts of Aristotelianism. The text of the *De Anima, Physics,* and *Posterior Analytics* set the bare bones of Aristotle's beliefs on the genesis of science in the

13. Einstein's analysis of light as photons had thrown the discussion of the wave particle theory wide open. De Broglie, we imagine, reasoned that the electron might have similar dual properties. Because electrons are so small, a very tiny aperture would be needed to be able to interfere with its waves. De Broglie explained how the space between atoms in a crystal ought to be of the right size. Experiments proved that electrons are diffracted by crystal lattices, just as if they are waves.

human mind. I believe that Duhem adhered rigorously to what he found in these works. On the other hand, the texts of scores of medieval philosophers evidenced bad Aristotelianism. Duhem was reinforced by these in his determination to resist all attempts to introduce alien factors into physical theory. Now I present Duhem's version of how to incorporate a good philosophy of nature, with its attendant epistemological considerations, into a correct analysis of what physics was, in his day. Most fundamental in his analysis is the role of the quantification of sensory data. This makes the regularities and the systematic aspects of natural processes most manageable in stating physical laws. It also makes physics a probabilistic endeavor that does not aim at explaining the material universe. By quantification Duhem means representing things by conventional quantitative symbols.

Representing kinds of things by conventional quantitative symbols eliminates the ambiguity of other conventional signs and makes possible the use of strict rules of calculation. Thus every sense quality can be represented by arbitrary symbols, which, being able to signify more and less of the same thing, can represent variations in the intensity of the quality in a very precise way. Causes producing the quality or effects produced by the quality may be suitably quantified, should the quality itself prove difficult to measure. Duhem gives the example of the expansion of mercury in a thermometer as a measuring of the heat surrounding it.[14] The expansion of the mercury is due to the activity upon it of heat, which is equated with the motion of the surrounding molecules adjacent to the glass of the thermometer. Analyzing the motion of molecules is difficult in itself, but it gives rise to an effect that is measurable to some extent. The measuring involves a translation of the physical circumstances into numbers, by the use of measurement. The temperature may be read as 10 degrees or as 9.9 degrees or as 10.01 degrees, and so on, depending on the accuracy built into the thermometer. These are the translations that quantify the effect of the molecular activity. They replace the language of the sensory awareness of warmth by the language of numbers. There is no replication of warmth as such in the 10 degree reading. What is replicated is the amount of heat, only the quantity. It suffices, for ascertaining someone's body temperature, to know how close it is to the accepted norm. A certain amount of deviation is tolerable. A larger deviation is cause for alarm. Approximation tells us what we need to know. We fit the meaning of the deviation into the rest of our estimation of the situation and act accordingly. However, if we were cal-

14. Duhem, *Aim*, pt. 2, chap. 1, 115–16.

culating how a variation in temperature affected the pressure exerted by a gas upon the walls of its closed container, we would be trying to get the most accurate information possible, so as to state the numerical relation between the measure of the temperature and the measure of the pressure. These measures tell us something that is quantitatively true about the gas and the heat applied by approximately replicating their real quantitative aspects. The more accurate the measure the more it replicates the real quantities involved. This scientific knowledge does inform us reasonably accurately about matter. The version of the gas laws involved here does state a real relationship between temperature and pressure and volume, real but still approximate.

Physical reality was lost in the translation inasmuch as that reality is now represented by an abstract symbol that replicates only the quantitative aspect of the physical. Remember Aristotle's telling us that we can separate the quantitative in our consciousness, but nothing real exists as just quantity. Our instruments do indeed report on just the quantitative in many instances, but no one has ever experienced blank quantity in nature or in any other medium but thought. Duhem sees in this lack of correspondence between the symbolized and the symbol a loss of ability of a physical theory to interpret the meaning of what it has collated. It can deal with the physical laws that state the order and the causal dependencies that are found in nature. But any meaning beyond what they reveal in being ranked and correlated must be found outside the physical theory. Its method, which it must follow in order to achieve a precision greater than is found in our everyday knowledge of things, cuts it off from that realm of common sense from which it began. The transforming of sensed sensibles into quantified data eventually yields a highly abstract intelligibility, which is the glory of science. That intelligibility is a most powerful tool for looking at reality once again and seeing order and system and causal connections where before there was only a hodgepodge. The mind can read right into our sensory observations its judgments about the way things are, including causal connections. But the power of physical theory is less than the power of mind. Although it has phenomenal ability to explain in the domain where evidence is certain, it cannot, Duhem tells us, go beyond the appearances that our senses register repeatedly without betraying its goal, the correct classification and collating of physical laws. Mind can transcend the limitation of physical theory by going altogether outside the range of what it is sure of. But then mind is not doing physics.

Although Duhem's series of articles on the nature of physical theory were roughly concomitant with the three famous articles by Einstein written between the middle of March and the end of June in 1905, neither author acknowledged the other. Nevertheless it was by sweeping away unfounded presuppositions about subvisible factors, supposedly involved in heat and light phenomena, that Einstein explained both blackbody radiation and the photoelectric effect in a quantum mechanical way. In similar vein, Heisenberg and Schrodinger and Dirac developed quantitative ways of analyzing the data about the subvisible by leaving aside every aspect of sensed or imagined reality. Thus Duhem's analysis of how to do physical theory, by abandoning the qualitative aspects of matter and sticking to the measurable, is a truism in serious physics today. What is an electron? It is a particle that is characterized by its mass, and its electric charge, and its wave-like properties. It, like other components of chemical atoms, is known as a momentum having an intrinsic angular spin. It is described by four quantum numbers and is the workhorse of the workaday world.[15] It is electric current; it, along with the positive holes resulting from a scarcity of electrons, is solid-state electronics; it is the carrier of the energy involved in chemical reactions; it is the massive currents miraculously carried by superconductors. That the electron is what it does is the only description that we have of it beyond estimating its mass and charge. The other "little things" of today's physics are similarly apprised by deducing and measuring their quantitative aspects. Duhem is right: all we can be sure of are the measurable aspects of what we are working with.

Duhem was stating what he understood to be a fact about how one does physics successfully. The disappearance of the unmanageable qualitative aspects of things is a boon to the required precision of the quantifying process. It also should prevent the wrongheaded attempts to visualize the underlying stuff of things. The quantified results of experiment, and of observation, were safe and sufficient indications of physical reality. Of course, hypotheses went beyond observation. But in a well-constructed physical theory they are not just wild imaginings of possible substrates. Rather they are the sine qua non of physical theory. They not only express in a highly condensed form all of the phenomena expressed in concise fashion by an array of physical laws but also allow the deduction of lawlike behavior not otherwise suspected.[16] Dirac's reasoning to the existence of antimatter, as an implication of $E^2 = M^2C^4$ having a negative root, $-MC^2$, would have

15. Emilio Segre, *From X-Rays to Quarks* (New York: W. H. Freeman and Company, 1980). The discoveries of Rutherford, Bohr, Einstein, Heisenberg, and others, form the chapters of this very readable book.

16. Duhem, *Aim*, pt. 1, chap. 1.

pleased Duhem mightily. It is a vindication of his belief that successful physical theory approaches ever closer to a complete classification of all the laws of physics. This in turn is a replication, although still with a lack of fit, of the real physical world.

Duhem was more apologetic about his natural classification than he needed to be. As an Aristotelian he saw the growth of physical knowledge as making man ever wiser about his world. The uniformities of nature, the causal dependencies, the successful extrapolations constantly expanded man's comprehension of his surrounds. However, as a mathematical physicist, he saw a failure of physical theory to replicate natural things truly as they actually existed. And so, it was as an act of faith that he concluded that physical theory would arrive at a complete classification of the laws of nature.

But a short sketch of how a physical theory does its proper work leads to a different conclusion, and there is substantial evidence to show that Duhem was right. The first step in setting up a physical theory, Duhem says, is to find what is basic, find what is reliably repeatable in our field of observation. To achieve complete economy of thought, analysis of complexes into their constituent parts should arrive at the smallest number of primitive notions. As Aristotle had said, we are on the way to scientific knowledge when we determine the principles and simplest elements of the objects of inquiry. However, as Duhem points out, what is taken for simplest and basic will depend on the state of the art at any given time.[17]

The correlation of the primary factors into physical laws brings a large group of phenomena into explanation. That is the value of science. More thorough analysis or a new discovery may enlarge the scope of the scientific explanation. Duhem uses Maxwell's reduction of white light to electromagnetic activity, as an instance of enlarging the scope of Maxwell's equations, to include a phenomenon waiting to be classified, into a category already established.[18] Duhem sees the process as a constant dialogue between the factual certainty, in the realm of observation and experiment, and the precision and clarity, afforded by quantification and mathematical deduction.[19] In optics the mind of the physicist funnels the facts into laws, which then give a concise representation of a whole area of optical phenomena. These laws are then integrated into an optical theory, from which, by calculation, one can draw out whatever law one wishes to use. As experiment and observation reveal more of a factual nature, the theory incorporates them and probably adjusts somewhat in order to do so.

17. Duhem, *Aim*, pt. 2, chap. 2, 3.
18. Ibid.
19. Duhem, *Aim*, pt. 2, chap. 7, 5.

The correspondence between the theory and the facts grows to the point where there are no known exceptions. But Duhem had been too impressed by the approximate aspect of physical law. It can be a problem, but human ingenuity has constantly surmounted it. Smaller and smaller quantities are constantly being matched by ever-finer measurements. Nanoseconds and picoseconds are measured easily in today's superb optics, and the waves of electrons are being utilized in chip technology.[20] Approximation to reality is not an insurmountable barrier to our cataloguing of nature. In some areas, such as the periodic table of chemical elements, the classification of the elements that occur in nature is fairly complete. The interrelations between their structures are adequately expressed in terms of protons, neutrons, and electrons. Principles that had at one time been proposed as tenable hypotheses are now firmly stated as physical laws. Duhem foresaw the outlines of the physical theory that is being developed and used today.

20. *High Technology*, vol. 9, no. 3, p. 32, on ten-picosecond computing; p. 9 on use of electron waves in resonant-tunneling transistors.

Publication of this book has been funded in part by a gift to the Associates of The Catholic University of America Press by Msgr. Edward A. Synan.

The paper used in this publication meets the minimum requirements of American National Standards for Information Science—Permanence of Paper for Printed Library materials, ANSI Z39.48-1984.
∞

LIBRARY OF CONGRESS CATALOGING-IN-PUBLICATION DATA
Nature and scientific method / edited by Daniel O. Dahlstrom.
p. cm. — (Studies in philosophy and the history of philosophy ; v. 22)
Includes bibliographical references.
1. Science—Methodology. 2. Science—Philosophy.
3. Philosophy of nature. I. Dahlstrom, Daniel O.
II. Series.
B21.S78 vol. 22
[Q175.3]
100 s—dc20 89-70817
[502.8]
ISBN 0-8132-0723-1 (alk. paper)