ERNST MACH AND PIERRE DUHEM ON PHYSICAL THEORY

This BOOK examines two variations on positivism formulated by two turn-of-the-twentieth-century physicists, Ernst Mach and Pierre Duhem. And it previews the story of positivism's rejection by the physicists who made the two great scientific revolutions in twentieth-century physics, Einstein and Heisenberg.

Mach's Phenomenalism

Ernst Mach (1838-1916) is a representative figure of the early positivist philosophy of science in physics at the turn of the twentieth century. He earned a doctorate in physics from the University of Vienna in 1860, taught experimental physics for most of his career at the University of Prague (1867-1895), and then held the chair of Inductive Philosophy at the University of Vienna (1895-1901). He was several times nominated for the Nobel Prize. He set himself the philosophical task of implementing the phenomenalist philosophy of David Hume in physics while Newtonian mechanics still prevailed in physics.

Prior to contemporary pragmatism philosophers based their philosophies of science on one or another metaphysical viewpoint. Though positivists philosophers including Mach were explicitly "antimetaphysical" (Mach even denied that he was a philosopher), they were actually advocating their own metaphysics while labeling the views they opposed as "metaphysical", and used the term pejoratively. Positivism is a philosophy that evolved in reaction against the various romantic philosophies, and what the positivists meant by "metaphysics" was the metaphysics of the romantics. Just as the views of the romantics evolved from the philosophical tradition of the rationalists, similarly those of the positivists evolved from the tradition of the empiricists. Thus Mach's epistemology is very similar to the views of the empiricists Berkeley and Hume, and he explicitly expressed indebtedness to them in his works.

Mach's principal work setting forth his phenomenalist philosophy is his *Analysis of Sensations* (1885), which went through five editions in both German and English, although Mach also discussed his epistemological views in many of his other works. His epistemology postulates "elements" such as individual sounds, temperatures, pressures, spaces, times, and colors. When these elements are considered in relation to one another, they are studied by the physical sciences, and when they are considered in relation to the human mind or rather the nervous system of the human body, they are called "sensations" and are studied by psychology.

One of the central theses of Mach's *Analysis of Sensations* is that the only difference between elements and sensations is the aspect under which they are viewed, and that physics and psychology therefore have the same subject matter. The distinction between the physical and the psychical is entirely a matter of convenience or practicality, because everything is merely a function of these elements. Everything other than these elements is a mental construct consisting of complexes of sensations. All material things including our own bodies and even the ego are nothing but complexes of elements that are constructs made by the human mind and that have some fixedness or constancy in sense experience.

A fundamental thesis of Mach's philosophy is that material bodies do not produce sensations, but rather complexes of sensations are associated together by the human mind to produce material bodies. Ultimately all that is valuable in science is the discovery of functional relations of dependency of sensations upon one another. The constancies that enable our mental construction of physical bodies have no privileged reality status. This is even more so with such mental constructs as the physicists' molecules and atoms, which are mental constructs that unlike those of physical bodies are not found in experience. The positivist phenomenalist philosophy is a nonrealist metaphysics, and if it is generously said to have an ontology, the ontology consists merely of the phenomenal elements/sensations.

Mach's Philosophy of Science

Aim of Science

Mach's philosophy of science is rich enough that it addresses all the four basic topics conventionally considered in a philosophy of science: the aim of science, discovery, criticism and explanation. He offers several statements of the aim of science. One sets forth the "biological task of science", which is to provide the fully developed human individual with as perfect a means of orienting himself as possible. In a second statement he says that the aim of all science is the representation of facts in thought either for practical purposes or for removing intellectual discomfort, since every practical and intellectual need is satisfied when our thoughts can represent the facts of the senses completely. He adds that our knowledge of a phenomenon of nature is as complete as possible, when thoughts are set before the mind's eye such that all the relevant sensible facts can be regarded as a substitute for the phenomenon itself. Then the facts appear to be familiar and are not able to occasion any surprise. In a third statement he says that the goal of science is the simplest and most economical abstract expression of facts. The noted economy of science involves uncompleted facts, judgments or laws. The last two statements of the aim of science are contained in Mach's philosophy of scientific explanation.

Scientific Explanation

Mach set forth his theory of scientific explanation in many places including his *Analysis of Sensations*, his "The Economical Nature of Physical Inquiry" (1882) and "On the Principle of Comparison in Physics" (1894) reprinted in his *Popular Scientific Lectures* (1898). He says that explanation is the economical description of experience in terms of elements. When we examine facts for the first time they appear confusing. In time we discover simple stable elements out of which we can mentally construct the entire factual domain, and when we have reached the point where everywhere we can discuss the same facts with other persons, then we no longer feel lost and the phenomenon is explained. The explanation offers a survey of a given domain of facts with the least expenditure of thought. The representation of all the facts of a domain by one single mental process is economical. He adds that the greatest perfection in mental economy occurs when science uses mathematics.

Not all descriptions are explanations; only direct descriptions can be explanations, while theories on the other hand are indirect descriptions and are not explanations. Direct descriptions may be either complete or incomplete. Description of what is presently observed is a complete description. Incomplete description refers to what is presently unobserved but observable and what is associated by a law, as for example the movement of a comet that is presently unobserved or the body of a man who disappears behind a pillar. The incomplete description can be completed by the human mind by means of the associations made by a scientific law. A direct description is one in which a single feature of resemblance among facts is called from memory, while a theory such as the description of light as a wave motion is an appeal to another description that had previously been made elsewhere. A theoretical idea offers more than what we actually observe in a new fact. It can be used to extend a fact and enrich it with features, which we are firstly induced to seek from its suggestions and, which are often actually found. A theory may lead to discoveries, but the adoption of a theory always carries a danger: even the most fruitful theory may be an obstacle to inquiry. By way of example Mach says the theory that light is an undifferentiated straight line of particles impeded the discovery of the periodicity of light. The ideal of a given domain of facts is direct description; such description accomplishes all that the scientific investigator could wish.

Scientific Criticism

In the *Analysis of Sensations* Mach states that he has taken Hume as his starting point, and this starting point is reflected in his views on scientific criticism. The scientist like everyone else knows the elements with complete certainty as sensations. But scientists and other persons also make judgments that are laws or generalizations. Since the aim of science is the adaptation of thoughts to facts, a new fact may require a new adaptation, which finds its expression in the operation of judgment. A judgment is the supplementing of a sensational presentation, in order to represent more completely a sensational fact. In the adaptation of thoughts to facts the adaptation can be made only to what is constant in the facts. Only the mental construction of constant elements can yield economy. But our confidence in the constancy in our judgments or generalizations rests entirely on the supposition, which in a given case has been substantiated by numerous trials, that our mental adaptation is sufficient. And we must be prepared to find this supposition contradicted at any moment.

Therefore empirical laws as well as theories are provisional in Mach's view, but for different reasons. The empirical generalizations are provisional, because they impute constancies to an infinite number of individual occurrences of sensations while only a limited number have actually been experienced. On the other hand theories postulate things that have never been experienced; no one for example has ever (in Mach's time) actually seen atoms or molecules nor has anyone ever experienced Newtonian absolute space or absolute time. Mach did not seem to find the provisional status of empirical laws to be very disturbing and in fact he considered laws to be necessary for science to have its economy. But he considered the provisional status of theories to be an unsatisfactory expediency for science. His philosophy of scientific criticism includes a phenomenalist criterion that rejects theories. Initially the logical positivists who followed Mach were reluctant to accept Hume's skeptical views on scientific criticism, and instead accepted the idea of "verification", the view that scientific laws or empirical generalizations can be established in some permanent sense, an idea that historically had been definitive of truly scientific knowledge. But Carnap and the logical positivists moved toward Mach's acceptance of scientific laws as provisionally true instead of permanently true, even as they moved away from his phenomenalism.

Scientific Discovery

Unlike most other philosophers, Mach's concept of scientific discovery does not involve the idea of theory development. In his "The Part Played by Accident in Invention and Discovery" (1895) in his *Popular Scientific Lectures* Mach notes the importance of accident in invention and discovery, but maintains that the inventor is not passive. In fact Mach compares the discoverer to the artist. He says that no man should consider attempting to solve a great problem unless he has thoroughly saturated his mind with the subject, so that everything else recedes into relative insignificance. Then the discoverer can detect the uncommon features in an accidental occurrence and their determining conditions. Mach believed that it is the idea that dominates the thinking of the inquirer and not vice versa. The movement of thought obeys the laws of association, and in a mind rich with experience every sensation is connected with so many others that the course of thought is easily influenced by apparently insignificant circumstances, the accidental occurrence of which turn out to be decisive.

Therefore there is a *process* of discovery, and Mach considered how this process could be guided. He explicitly rejected any combinatorial approach as too laborious and extensive. The man of genius in Mach's view consciously or unconsciously pursues systematic methods, and in his deliberate presentiment he omits many alternatives and abandons others after hasty trial, alternatives on which less endowed minds would squander their energies. From the abundance of fancies that a free and active imagination produces, there emerges one particular configuration, which fits perfectly with a basic design or idea. Mach does not elaborate further upon this process; and while he believes that it may be guided, he does not propose any consciously repeatable procedure. Perhaps he could go no further in this investigation, because he also believed in *gestalt* qualities and accepted a wholistic view of complexes of sense impressions. In any event his belief that the process can be guided leads him to conclude that genius may be regarded as only a small deviation from the average mental endowment. He states that the way to discovery must be prepared long beforehand, and that in due course the truth will make its appearance inexorable as if by divine necessity. Apparently therefore he rejected the heroic theory of invention.

Mach's History of Mechanics

Mach's most popular work was his *Science of Mechanics: A Critical and Historical Account of Its Development* (1883) also known as *The History of Mechanics*. This book went through nine editions both in German and in English, seven of which were published in Mach's lifetime. The physicists whose works Mach examined were not phenomenalists, and he set out to write a critical history of mechanics from the perspective of his own phenomenalist philosophy of science. As he stated in the introduction to the first edition, the book's purpose is to clarify ideas, reveal the real significance of the matter, and to purge physics of its metaphysics. For Mach this agenda amounted to purging physics of theory. With this aim in mind he critiqued the contributors of the past as he salvaged and reconstructed what he found in their works to be of lasting value. Even the achievements of the great Isaac Newton did not escape his phenomenalist criticism unscathed. Mach criticized Newton's principle of reaction, his concept of mass, and his concepts of absolute space and absolute time. Starting from his own view that all phenomena are related, Mach concluded contrary to Newton that all masses, all velocities, and all forces are relative, a thesis known as Mach's phenomenalistic relativity. And he proposes his own set of definitions and empirical propositions to replace Newton's. The outcome of this criticism was to have a large impact on the histories of both philosophy of science and physics.

Duhem on Physical Theory and Metaphysics

Pierre Duhem (1861-1916), another important early positivist, studied physics at the Ecole Normale in Paris, where he received a doctorate in physics, and was a professor of physics at the University of Bordeaux for most of his career. His principal interest was physical chemistry, where he aspired to recast the theoretical foundations of chemical processes on the basis of a generalized thermodynamics. Unlike Mach, Duhem accepted the Aristotelian metaphysics, which he viewed as separate from positivist physics, and believed that progress in physical theory asymptotically approaches a "natural classification", which he equated to the cosmology of Aristotle. Duhem's philosophy differed from Mach's philosophy by the former's acceptance of physical theory as integral to physics, and by his development of a semantical metatheory to locate theory in positivist physics. The contemporary pragmatist philosopher Willard van Quine elaborated Duhem's semantical metatheory for mathematical physics into a general philosophy of language, and retrospection reveals that it has been Duhem's more lasting philosophical contribution.

Mach influenced Duhem who in turn also called his own philosophy of science positivist. But there were other intellectual influences in Duhem's thought, and as a result Duhem differed from Mach in at lease two important respects: firstly Duhem accepted scientific theory as a valid and integral part of science, and secondly he reserved a place in human knowledge for metaphysics. Mach's philosophy is often called "scientistic", by which is meant that only science offers valid knowledge and that no nonphenomenalist discourse, which is summarily called "metaphysical", is valid. While Mach was a physicist, philosopher, historian of science, and atheist, Duhem was a physicist, philosopher, historian of science and believing Roman Catholic. Like Mach, Duhem rejected the mechanistic, atomistic physics although for very different reasons than Mach. Unlike

Mach, Duhem wished to retain the natural philosophy and cosmology of the Aristotelian and Scholastic philosophies upon which had been built the theology of his religion since Thomas Aquinas.

The outcome of these differences between Mach and Duhem is a complex philosophy of science that affirms and protects the autonomy of physics from any encroachment by metaphysics, while conversely affirming and protecting the autonomy of metaphysics from any encroachment by physics. This mutual isolation of physics and metaphysics is due to Duhem's view that on the one hand metaphysics, natural philosophy, and cosmology pertain to realities that are hidden and that underlie the phenomenal appearances accessible by the senses, while on the other hand physics pertains only to observed phenomena. Furthermore and contrary to Mach, Duhem maintained that theories are integral to physics and are valid science. The only criterion for scientific criticism of a theory, unlike a phenomenal description, is the theory's ability to make predictions that are correct with a sufficient degree of approximation, *i.e.*, correct within the range of indeterminacy produced by a degree of measurement error that always exists in experimental data. Thus when Duhem rejected mechanism, one reason that he gave is that no mechanical atomic theory has been found to be sufficiently accurate, when judged by his purely scientific criterion for the criticism of theories.

But his principal reason for saying that the autonomy of physical theory is protected from the metaphysical thesis that physics must be mechanistic, is that physical theory has a special semantics that forbids interpreting the hypothetical postulates realistically, even if a proposed mechanistic hypothesis were scientifically adequate. Physical theory in Duhem's view can never have a realistic semantics. No metaphysical or cosmological philosophy may be called upon to supply theoretical physics with its axioms. For this reason Duhem denies that physical theory has any explanatory function in science; only metaphysics is able to "explain", and metaphysics has no place in physics. The distinctive semantics of physical theory is a very strategic part of Duhem's philosophy of science. His religious and other intellectual influences may have operated in his developing this distinctive philosophy of science, but his stratifying the semantics of the language of science into the realistic and the nonrealist has as its basis, reasons that are entirely integral to his concept of empirical science itself. These reasons are semantical, and must be examined before attempting an exposition of his philosophy of science.

Duhem's Stratified Semantics for Physics

As mentioned above, the second respect in which Duhem differs from Mach is the former's views on physical theory, and the difference is the most distinctive and lasting aspect of Duhem's philosophy of science. Mach had rejected theory as "metaphysical", meaning nonphenomenalist, and he maintained that ultimately in the ideal state of science all theory would be eliminated from science. Duhem's alternative view is set forth in his *Aim and Structure of Physical Theory* (1906). In this work as well in other works he not only recognized a valid metaphysics distinct from science, but also considered theory to be characteristic of science in its highest state of development. Over and above the economy that Mach saw in the empirical laws of science, Duhem furthermore saw an additional economy offered by theory. Physical theory is a hypothetical axiomatized system of equations that orders the multiplicity of experimental laws by means of a symbolic structure, which is not identical with the empirical laws but which "represents" them in a parallel language.

This symbolic structure consisting of the axiomatized mathematical system, which constitutes the theory, is a distinctive language in science. It is different from all other language of science including the realistic semantics of common discourse, the nonmathematical generalizations of descriptive sciences such as physiology, and the phenomenalist semantics of mathematically expressed empirical laws of science such as Kepler's laws. The language of theory is distinctive from nontheory language, because the nontheory language has a semantics that describes either the phenomenal or real world, while the language of theory does not have these semantics. Instead the semantics of theory language is called "symbolic", which means that its meaning is a sign of the meanings of the nontheory language. Thus the semantics of science in Duhem's philosophy is stratified into two levels, in which one represents the other.

The basis for Duhem's distinguishing the semantics of theory language from that of all other language is the existence of a numerical indeterminacy caused by the fact that measurements, which may occur in the equations of theory, are always approximate. There are two reasons for the indeterminacy between the equations of theory and the nontheoretical language. The first reason is simply the approximate character of all measurements. When measurements are made, a “translation” must also be made from what Duhem called a “practical” fact to a “theoretical” fact. The practical fact describes the observed phenomena and circumstances of the experiment; the theoretical fact is the set of mathematical data that replaces the practical fact in the equations of the theory. Duhem calls the method of measurement the dictionary that enables the physicist to make this translation.

For any practical fact there is always an infinity of potential theoretical facts, even when the degree of indeterminacy is reduced with improved instruments and measurement procedures. So long as the one or several equations of a theory are correct, the numbers that are the solution set for the equations will fall within the range of measurement indeterminacy. Duhem illustrates the semantical duality caused by this numeric indeterminacy in his discussion of the different meanings of the phrase “free fall.” One meaning is contained in a phenomenal description given by any person who knows nothing about physical theory. And a second meaning occurs in the physical theory that includes the idea of uniform acceleration. These are two distinct meanings; the former may be either a realist or phenomenalist meaning, while the latter is called the symbolic meaning. The latter is a sign of the former, so long as the theory is accurate enough to be accepted as true.

However, the numerical indeterminacy that occasions the semantical distinction between practical facts and theoretical facts is not unique to the variables occurring in the equations of theories, the equations that are the conclusions drawn from the hypotheses which are the postulates of the theory. It also occurs in the variables occurring in the equations of empirical laws, the equations that are developed by experimental or other observational judgments. This creates another occasion for numerical indeterminacy, one which exists between the values of the variables in the equations of theory and the values of the corresponding variables in the equations of the empirical laws that a theory orders. Duhem discusses this numerical indeterminacy and the semantical duality to which it gives rise, when he criticizes Newton’s claim that his theory of gravitation is not based on hypotheses.

The basic question is whether or not Newton's theory was or could be developed empirically by generalizing from Kepler's laws. Duhem argues that Newton had actually created hypotheses, because the mathematical deduction from these hypotheses produces conclusions that formally contradict Kepler's observational laws. In other words the solution sets for the empirical law and for the theory are not the same. Kepler's laws are approximate, and therefore admit to an infinity of small deviations. The measurements by Tycho Brahe permit the theorist to choose a variation of Kepler's laws, which is also produced by deduction from Newton's theory. Just as there must be a translation from practical facts to theoretical facts resolving the indeterminacy in measurements, so too there must be a translation from empirical laws such as Kepler's laws to "symbolic" laws such as Newton's dynamics. Here again the numeric indeterminacy causes a semantic dualism, and a translation is made in which the new symbolic formulas derived from Newton's hypotheses, are substituted for the old phenomenalistic formulas, which are Kepler's observational laws.

Having shown that there are different semantics for theory and nontheory language in science, Duhem then gives two ways in which the meanings of the symbols in theory language differ from the meanings in all the other language of science. The first way, which is most important to him, is that the semantics of theory language is neither realistic nor phenomenalist; it does not describe the world of phenomena as does the semantics of empirical laws like Kepler's laws, nor does it describe the real world as does the semantics of common-sense discourse. When Duhem states, therefore, that theories represent laws, he means to be taken literally; he means that theories do not represent the world but instead represent the empirical statements, which in turn represent the phenomenal world. Thus he cannot be called an instrumentalist in the sense that he denies that theory language has any semantics. He has stratified the semantics of science such that theory has its own higher level semantics.

He also states that when a theory agrees with experimental laws to the degree of approximation enabled by the measuring procedures employed, and furthermore when the theory correctly predicts the outcome of an experiment before the outcome has occurred, then there is reason to believe that the theory is not merely an economical representation of the experimental laws. Such a theory is also a "natural classification" of these laws in which the logical order in which the theory organizes the experimental laws is a reflection of the metaphysician's ontological order that underlies the physicist's phenomenal order. However, professionally the physicist cannot pass judgment on this analogical apprehension of the underlying ontological order, because this order is the proper subject only of metaphysics or natural philosophy.

The second way in which the meanings of the symbols in theory language differ from those in the other language of science is that the meanings of theory are determined by their context, by the statements that constitute the theory itself. Therefore, according to whether the physicist adopts one or another theory, the variables in the symbolic law change their meaning, so that the law may be accepted by one physicist who admits one theory while it may be rejected by another physicist who admits an alternative theory. Duhem illustrates this contextual determination of meaning in theory language in his discussion of Kepler's observational laws and the symbolic laws of Newton's theory. The formulas that constitute Kepler's laws refer to orbits, but when they are replaced by the symbolic formulas that are deduced from Newton's dynamics, the symbolic law contains variables referring to forces and masses also. The translation from Kepler's laws into symbolic laws presupposes the physicist's prior adherence to the hypotheses of the theory. The contextual determination of the meanings of theories is Duhem's wholistic concept of theory, a concept that is strategic to his views about scientific criticism of theories. With his wholistic view he says theoretical physics is not like a machine but is more like an organism.

Finally it should be noted that although the higher level semantics of theory language is relatively remote from the phenomena described by the semantics of the nontheory language, nevertheless theory is not remote from the experimental situation. He states that an experiment in physics is not simply the observation of a phenomenon, but is furthermore the theoretical interpretation of it. And this theoretical interpretation is not just a technical language, but one that makes possible the use of instruments.

He illustrates this distinction between observation and interpretation in physical experiment by offering two descriptions of an experimental apparatus in a laboratory. One description is given in the vocabulary of the physicist who understands the theory of electricity, and the other description is given in the observational language of the observer innocent of such theoretical understanding. The experimenting physicist actually has two distinct representations of the instrument in his mind. One is the phenomenal image of the concrete instrument that he manipulates in reality. The other is a schematic model of the same instrument constructed mentally with the aid of the symbols from the theories that the physicist accepts. Without knowing the theories that the physicist regards as established and that he uses for interpreting the facts he observes, it is impossible for anyone to understand the meaning he gives to his statements. And when a physicist discusses his experiments with another physicist, who accepts an alternative theory, it is necessary for the two physicists to seek to establish a correspondence between their different ideas and then to reinterpret the experiment.

Twenty years before the development of the quantum theory Duhem cited as an example the two alternative theories of light: Newton's emission theory and Frensel's wave theory. He maintained that the observations and experiments interpreted in the concepts of one theory could be translated into the concepts of the other theory. In his philosophy this is possible, not because he anticipated quantum theory, but because he was a positivist, who believed that the two theories could be related to a common theory-neutral phenomenalist semantics.

Duhem's stratification of the semantics of the language of theoretical science is central and strategic to his philosophy of science. It is not surprising that he stated that the approximate fit between measurements and theory creates a semantical difference. Haavelmo did the same thing for his theory of econometrics forty years later. But it might seem more correct were he to have said that the resolution of the indeterminacy in measurement by the calculated value for a variable in a theory actually resolves a semantic vagueness instead of saying, as he does, that it creates two distinct meanings. But it is surprising to find him concluding that the distinct meaning of the symbol in the theory is a "sign" of the phenomenal meaning defined by the experimental measurement method. It is this latter position that stratifies the semantics of science, so that theory cannot be given a realistic or phenomenalistic interpretation.

Nonetheless Duhem has a reason for taking this position. In his "The Physics of a Believer", an appendix to *Aim and Structure of Physical Theory*, he reports that earlier in his career he attempted unsuccessfully to conform to Newton's methods set forth in Newton's "General Scholium". He concluded that physical theory is neither a metaphysical explanation nor a set of general laws, whose validity is established, but rather that theory is an artificial construction manufactured with the aid of mathematical magnitudes. Thus the relation of the magnitudes to the abstract notion emergent from experiment is that of sign to thing signified. The key concept seems to be the idea of artificial construction. The artificial nature of theory gives it an artificial semantics, and this artificial semantics is of a different kind than the natural semantics of language that describes the phenomenal world.

Throughout most of the history of philosophy, philosophers believed that while the multiplicity of languages argues for the existence of a conventional aspect in human language, still, as Aristotle said, while men speak different languages, they have the same cognitive experiences. This is the thesis of a naturalistic semantics; all men have the same cognitive experience when in the presence of the same reality, because there is a natural relation between knowledge and reality. Mach's theory of sensations and of their identification with elements of the phenomenal world is a contorted variation of this thesis. But Duhem could not fit this thesis to the language of physical theory, even while he, like Mach, maintained it for the language of observation. He viewed physical theory as so artifactual that its meanings could not be natural but had to be artificial. Thus physical theory does not describe either the real or the phenomenal world of nature; it only describes symbols. But he was not led to conclude that theory is meaningless. His reconciliation strategy was to make the artificial semantics of theory describe the language of science, in effect a metalanguage.

Duhem's Philosophy of Science

Aim of Science

Duhem's statement of the aim of science is similar to Mach`s: the aim of science is economy of thought. Like Mach, Duhem believes that experimental laws contribute an intellectual economy, because they summarize a large number of individual facts including data measurements. But unlike Mach, Duhem furthermore says that theories also contribute to the realization of the aim of science. The economy achieved by the substitution of a law for individual facts is redoubled for the mind, when the mind substitutes theories for the numerous mathematically expressed experimental laws. A theory is a system of mathematical propositions mathematically derived from a small number of principles, which aim to represent as simply, as completely, and as exactly as possible, a set of experimental laws. Its aim in other words is economy of thought by schematically representing and logically organizing experimental laws.

Scientific Criticism

Duhem developed a sophisticated theory of scientific criticism, and it is central to his philosophy of science. He is very emphatic in defending the autonomy of empirical science from any encroachment by metaphysics or natural philosophy. Metaphysics pertains to realities that underlie the phenomenal appearances hidden by the phenomena, while science pertains only to these appearances. Consequently whatever may be the criteria and procedures for criticizing a metaphysical thesis, they are not relevant to empirical science. In empirical sciences that are nonmathematical, the generalizations such as “Every man is mortal” may be accepted or rejected as simply true or false. But in mathematical physics the equations both of the empirical laws and of the hypothetical theories are not simply regarded as true or false, but are approximate. The amount of underdetermination due to the approximate nature of the values of the variables in these equations will be reduced as experimental and measurement techniques improve. And because measurement instruments depend on physical theory, the improvement in instruments occurs due to the improvement in theory. As the range of this indeterminacy becomes smaller, the equations of either the empirical laws or the hypothetical theories that represent the laws may no longer be able to predict values for their variables that fall within the smaller range of measurement error. When this happens, the equations are no longer satisfactory. Duhem maintains that the only criterion that may validly operate in scientific criticism is the ability of the law or theory to make accurate predictions. This exclusion of all prior ontological or metaphysical criteria from scientific criticism has been carried forward into the contemporary pragmatist philosophy of science. It shows up for example as Quine’s rejection of all “first philosophy.”

In his theory of scientific criticism Duhem rejected the use of so-called crucial experiments as a means of establishing the validity of a theory. His thesis is that if the physicist is confronted with several alternative theories, the rejection of all but one cannot imply the establishment of the remaining one. As an example he cites the two alternative theories of light: one theory is the hypothesis that light is a stream of high speed projectiles, and the other is the hypothesis that light consists of vibrations whose waves are propagated in ether. This is not an anticipation of the Copenhagen duality thesis; Duhem is thinking of the wave and particle theories as alternative theories. His position is that the choice is not mutually exclusive, because no one can ever enumerate completely all of the various hypotheses, which may pertain to a group of phenomena. He thus maintains that several alternative theories may fall within the range of indeterminacy of the measurement data and experimental laws, so that more than one theory may be satisfactory. This represents a pluralistic thesis about science, and in the crucial experiment discussion, it means that even if all hypotheses could somehow be enumerated, elimination could not leave but one to be considered as established. This pluralism is another aspect of his philosophy of physical theory that has been carried forward into the contemporary pragmatist philosophy of science.

His theory of scientific criticism also reflects his wholistic view of theories. This wholistic view not only makes the meanings of the mathematical symbols mutually determined by the context consisting of the equations of the theory, it also necessitates testing the theory as a whole together with all the hypotheses used in the experiment including assumptions about the measuring instruments. Thus if the prediction in the test is wrong, not only may the proposition being tested be at fault, but also the whole theoretical scaffolding used by the physicist. The physicist can never subject an isolated hypothesis to experimental test, but only a whole group of hypotheses. The only thing that the experiment reveals is that among all the theoretical propositions used to predict the phenomenon, there is at least one error. Thus the failure of the prediction does not inform the physicist where the error lies or reveal which hypothesis should be modified.

In Duhem’s view physics is not like a machine which lets itself be disassembled; the physicist cannot test each piece in isolation and then make adjustments to the isolated part found wanting. Duhem compares physics to an organism in which one part cannot be made to function except when the parts that are most remote from it are called into play. When there is a malfunction felt in the organism, the physician must ferret out through its effects on the entire system, the organ that needs to be remedied or modified without the possibility of isolating the organ and examining it apart. Duhem says that the physicist confronted with a failed prediction is more like a physician than a watchmaker.

Scientific Discovery

Duhem also has a philosophy of scientific discovery. Unlike Mach's view on discovery and invention in science, Duhem's is not principally a theory of perception and empirical generalizations. He anticipates later philosophers including the logical positivists with his emphasis on the language of science. For him scientific discovery is not reduced to noticing what had previously been overlooked in perception; for him discovery is also the construction of hypothetical theories.

The construction of a theory involves four successive operations: Firstly certain physical properties are taken as simple, so that other things are combinations of these simple properties. These properties are not simple in any absolute sense like Mach's elements, but are taken as simple only for purposes of the theory. The simple properties are measured, and the magnitudes are assigned to symbolic variables. Secondly the magnitudes are connected by propositions, *i.e.*, equations that are hypotheses, and that serve as postulates of the deductive system. Thirdly the postulates are not realistic or phenomenalist, but are freely created; using them requires only that the logic of algebra be correctly applied for making deductions. Fourthly the conclusions drawn from the postulates are compared with the experimental laws that the theory is intended to represent and organize.

If the conclusions agree with the laws within the degree of approximation corresponding to the measurements taken in the experiments, then the theory is said to be an acceptable theory. Such acceptable theory may in turn be used for the further development of measuring instruments used in experiments, as well as constituting the final product of the scientific endeavor with its maximum economy. Improved theory produces improved instruments, which in turn produce better measurements. These better measurements reduce the range of the indeterminacy in the numerical data, which may cause the theories to fail in their predictions. Such failure will occasion two types of responses. The initial response is to modify the theory with corrections, which will enable the predictions made with the theory to fall within the smaller range of indeterminacy produced with improved measurements. But these corrections also complicate the theory, and in due course "good sense" may lead some physicists to decide to refrain from adding more complicating corrections, and instead attempt to revise the hypothetical postulates of the symbolic schema, *i.e.*, of the whole theory itself. The accomplishment of such a revision is the work of the genius.

But Duhem does not subscribe to the heroic concept of invention; history creates the genius as much as the genius creates history. The physicist does not choose the hypotheses on which he will build a new theory; the theory germinates within him. This germination is not sufficiently explained by the contemplation of the experimental laws that the theory must represent. It is a larger cultural development. In due course when the cultural process that he calls universal science has prepared minds sufficiently to receive a new theory, it arises in a nearly inevitable manner. Often physicists who do not know one another and who are working great distances from one another, generate the same theory at the same time. In the course of his studies the historian of science according to Duhem often observes this simultaneous emergence of the same theory in countries far from one another.

Scientific Explanation

On Duhem's philosophy theories do not explain the laws nor do the laws explain the facts. Explanation is proper only to metaphysics and not to science. In the opening sentence of the introduction to his *Aim and Structure of Physical Theory*, Duhem says that he offers a simple logical analysis of the method by which physical science makes progress. While affirming the autonomy of physics with his thesis that agreement with experiment is the sole criterion of truth for a physical theory, Duhem has a distinctive concept of scientific progress, which he elaborates in the appendices to the book.

He says that there are two types of development in physics that are occurring simultaneously. One is what today would be called the revolutionary type of development consisting of a succession of alternative theories, in which one theory arises, dominates the scene for the moment, and then collapses to be replaced by another theory. The other is an evolutionary progress in which more ample and more precise mathematical representation of the phenomenal world is constantly disclosed by experiment. When the progress of experimental science goes counter to a theory and compels the theory to be modified or transformed, the purely representative part enters nearly whole into the new theory, bringing to it the inheritance of all the valuable possessions of the old theory, while the hypothetical part falls away in order to give way to another theory. The first type is identified with the mechanistic physical systems including Newtonian physics as well as Cartesian and atomic physics. The second type is identified with general thermodynamics, which Duhem believes will lead physical theory toward its goal.

Duhem believes that the goal of physics is the convergence toward an analogy with Aristotle's physics. He concludes in his discussion of the value of theory, that the physicist is compelled to recognize that it would be unreasonable to work for the progress of physical theory, if theory were not the increasingly better defined and more precise reflection of a metaphysics. He thus concludes his book with the thesis that belief in an order transcending physics is the ultimate metaphysical justification of physical theory.

Duhem's History of Physics

Just as Mach had written a history of physics viewed through the lenses of his philosophy of science, so too did Duhem. However, Duhem's effort was relatively monumental; it is a work originally intended to be twelve volumes of which ten were actually written before its author's death in September 1916. This *magnum opus* was his *System of the World: A History of Cosmological Doctrines from Plato to Copernicus.* The central thesis of this work is summarized in a much smaller book begun earlier, *To Save the Phenomena: An Essay on the Idea of Physical Theory from Plato to Galileo* (1908). His thesis is that the hypotheses of physics and especially the heliocentric hypothesis in astronomy are mere mathematical contrivances for the purpose of "saving the phenomena".

Pope Urban VIII condemned Galileo in 1633 for maintaining that Copernicus' heliocentric theory is not merely a mathematical contrivance, but is rather a description of the real world. Formerly known as Cardinal Bellarmine, this Pope maintained that regardless of how numerous and exact may be the confirmations of a theory by experience, these confirmations can never transform a hypothesis into a certain truth that can be taken realistically, since this transformation would require that the experimental facts should contradict any other hypotheses that might be conceived, a requirement that cannot logically be satisfied. Galileo, on the other hand, maintained that because Copernicus's theory saved the phenomena more adequately than any alternative hypothesis, the Copernican theory had to be a realistic one.

Contemporary pragmatists agree with Duhem's rejection of any prior ontological criteria for the criticism of scientific theory, but contrary to Duhem they furthermore agree with Galileo's practice of ontological relativity, *i.e.*, scientific realism. Contemporary pragmatists are realists, who let the most empirically adequate theory decide the ontology. Galileo's argument for realism is the same as Quine's doctrine of ontological relativity, and Feyerabend calls it the Galileo-Einstein tradition of realism. And Heisenberg invoked this tradition, when he referenced Einstein's realistic interpretation of relativistic time in the relativity theory, and then used it as a precedent for his own realistic interpretation of the quantum theory's duality thesis, notwithstanding Bohr's instrumentalist complementarity principle. Duhem, however, denied that theory is realistic, and he construed Galileo's argument as a case of the fallacy of the crucial experiment; he argued that it is impossible to enunciate all the possible hypotheses, and establish the truth of one by elimination of all others. The accomplishment that Duhem credits to Kepler and Galileo is the rejection of Aristotle's view that celestial and terrestrial physics are fundamentally different, and that hypotheses of physics must save all the phenomena of the inanimate world.

The New Physics vs. the Old Philosophy

The history of philosophy of science has been greatly influenced by the history of physics. As twentieth-century physicists found themselves departing farther and farther from Newtonian physics, they also found themselves departing farther and farther from the positivist philosophy notwithstanding the positivists' criticisms of Newtonian physics. At the beginning of the century positivism was not merely the academic philosophy it later became. It was for a time the working philosophy for many physicists including those who produced the revolutionary relativity and quantum theories. It achieved ascendancy in academia during the first half of the century, where it evolved into logical positivism with the introduction of the symbolic logic, which made it irrelevant to the practice of basic research in the sciences. But long before academia recognized positivism as a kind of latter-day decadent Scholasticism in the second half of the century, it had fallen into disrepute in the eyes of the physicists who encountered its fundamental inadequacy for the new physics.

In his "Autobiographical Notes" in Schilpp's *Albert Einstein* (1949) Einstein stated that Mach's *History of Mechanics* had exercised a profound influence on him when he was a student. He related that all physicists of the last century saw in classical mechanics a firm foundation not only for all physics but also for all natural science, and that it was Ernst Mach who with this book shook Einstein's dogmatic faith. At sixty-seven years of age, when he was writing these autobiographical notes, Einstein saw Mach's greatness in the latter's incorruptible skepticism and independence, even though Einstein himself had since rejected Mach's philosophy. Einstein was specifically influenced by Mach's critique of the Newtonian concept of absolute space, time and motion, ideas that are also rejected in Einstein's relativity theory. Initially Mach seemed to support Einstein's views. But Mach and Einstein were fundamentally working at cross purposes: Mach attacked the Newtonian concepts of absolute space, time and motion as part of his critique of all theoretical physics, while Einstein discarded these Newtonian ideas as a means for developing a new theoretical physics.

Another influence on Einstein was a thought experiment that Einstein reports he imagined, when he was sixteen years of age. In this thought experiment Einstein wondered what would happen if an observer traveled at the speed of light, riding on a beam of light. The light would then be at rest relative to the rider, but Einstein concluded that the idea of a light beam at rest is self-contradictory. This thought experiment was imagined many years before Einstein was introduced to Mach's book by his friend Besso, while they were students at Zurich, and Einstein reports that it contributed to his forming the idea that the velocity of light in a vacuum is constant in all reference systems. From the positivist view the constancy of light is no less objectionably absolute than the concepts of absolute space or time. Mach's phenomenalist relativity states that all sensations are dependent on all other sensations, while Einstein's relativity theory states that the velocity of light in a vacuum is independent of other phenomena.

Throughout Mach's lifetime Einstein continued to view his relativity theory as a continuation of Mach's philosophy, and in his obituary of Mach in 1916 Einstein expressed the opinion that Mach would have come across the theory of relativity, if when Mach was younger the constancy of the velocity of light had been accepted by physicists. In 1921 Mach's son published his father's *Principles of Physical Optics*. The preface of the book is dated July 1913, and in it the son reports that Mach opposed Einstein's relativity theory, and he rejects the idea that his father was a forerunner of relativity theory. As it happens, in June of 1913 Einstein had sent Mach a preliminary draft of the general theory of relativity, which uses non-Euclidian geometry. But in the 1912 edition of his *Science of Mechanics* Mach had introduced a lengthy footnote (Ch. IV, Sec IV, 9) opposing Minkowski's use of four-dimensional geometry in physics and stating that the space of sight and touch is three-dimensional. It is unlikely, therefore, that Mach was pleased when he received Einstein's 1913 correspondence, and it may have provoked the comments in the 1913 preface to the book on optics. Eventually Einstein accepted the existence of basic differences between his relativity theory and the positivist philosophy of Mach, and he ultimately rejected Mach's philosophy.

Einstein's general theory of relativity departed even further from Mach's philosophy than did the special theory of relativity, because in the general theory it is not possible to restrict the equations to relations among observable magnitudes. But as the theory became accepted among physicists, the positivists who followed Mach did not want to reject it, and instead they modified their philosophy. These later neopositivists or "logical" positivists, as the positivists of the Vienna Circle came to be known, replaced Mach's rejection of theories with a less restrictive idea. They said that the language of science might contain theoretical terms referring to nonobservable entities and magnitudes, on condition that statements referring only to observables could logically be related to those that contain these theoretical terms referring to the nonobservable magnitudes or entities. This later positivist program is considered below in the discussion of the logical positivists including Rudolf Carnap. Mach eventually accepted Einstein's relativity theory, and also persuaded Moritz Schlick, founder of the Vienna Circle and successor to the chair of inductive philosophy previously held by Mach at Vienna, to accept Einstein's theory. With this acceptance of Einstein's relativity theory one of the basic theses of the early positivist philosophy was changed.

Positivism was not without some influence on the contributors to the new quantum physics, whose views became known as the "Copenhagen interpretation." Adherents to this Copenhagen interpretation included 1922 Nobel-laureate Niels Bohr, 1932 Nobel-laureate Werner Heisenberg, and 1945 Nobel-laureate Wolfgang Pauli. Its opponents included 1921 Nobel-laureate Albert Einstein, 1933 Nobel-laureate Erwin Schrödinger, 1918 Nobel-laureate Max Planck, 1929 Nobel-laureate Louis de Broglie and David Bohm. The member of Bohr's Institute for Theoretical Physics in Copenhagen, Denmark, who was initially influenced by the positivist philosophy, was Werner Heisenberg. In his *Physics and Beyond* (1971) Heisenberg relates how Mach's philosophy operated in his own thinking. In the chapter titled "Understanding in Modern Physics (1920-1922)" he described his positivist views during the years that preceded his development of his matrix mechanics. At that time he believed that true understanding in physics consists in using only language that refers to direct sense perceptions, and that while the ability to make correct predictions is often a consequence of this positivist kind of understanding, nonetheless making correct predictions is not the same as having true understanding. Because he accepted the positivist philosophy of science, Heisenberg rejected Bohr's hypothesis of electron orbits, since the orbits are not observable, but unlike Mach he admitted the existence of the electron itself due to the observable tracks produced by the free electron in the Wilson cloud chamber experiments. The cloud chamber developed by C.T.R. Wilson in 1912 consists of a container with a saturated vapor under pressure. When the pressure is rapidly reduced, the vapor cools and becomes supersaturated, as the temperature drops below the dew point. The passage of a charged particle, *i.e.*, an electron through the vapor causes ion pairs to form droplets. A string of these droplets produces the track of the charged particle.

In the chapter titled "Quantum Mechanics and a Talk with Einstein (1925-1926)" Heisenberg relates that on the day that he presented his matrix mechanics to the Physics Colloquium at the University of Berlin, Einstein, who was present in the assembly, expressed interest and invited Heisenberg to talk with him at his home that evening. The matrix mechanics does not postulate the existence of electron orbits around the nucleus of the atom, and when Einstein questioned Heisenberg about his positivistic views that evening, Heisenberg replied that he did not believe that postulates about orbits are appropriate, because the orbits are not observable. Heisenberg affirmed the view that the physicist should consider only observable magnitudes, and for that reason he developed the matrix mechanics, which treats only of the frequencies and amplitudes associated with the lines in the spectrum of the atom. Heisenberg also stated that he was using the same philosophy that Einstein had used, when the latter had rejected the concept of absolute space and time in developing relativity theory.

Einstein then replied that he no longer accepted the positivist view, because **the physical theory decides what the physicist can observe**. This idea that theory determines what is observed is philosophically very strategic, because it contradicts the underlying positivist assumption that there is a dichotomous distinction between the descriptive language about what is observable on the one hand, and the theoretical language about what is not observable on the other hand. When this dichotomy is denied, the positivist program of building science on firm foundations of observation is rendered untenable.

In the chapter titled “Fresh Fields (1926-1927)” Heisenberg describes the arguments between Niels Bohr and Erwin Schrödinger concerning the issue of the wave verses the particle views in microphysics and of the statistical approach taken by 1954 Nobel-laureate Max Born in 1927. Born maintained that Schrödinger’s wave function can be construed as the measure of the probability of finding an electron at a given point in space and time. Heisenberg accepted Born’s probability interpretation, but there still remained a problem in Heisenberg’s mind: Born’s interpretation did not explain how the trajectory of an electron particle in the cloud chamber could be reconciled with the wave mechanics. Particle trajectories did not figure in the matrix mechanics, and wave mechanics could only be reconciled with the existence of a densely packed beam of matter if the beam spread over areas much larger than the diameter of an electron.

With this problem in mind Heisenberg remembered his conversation with Einstein the previous year, specifically Einstein’s statement that it is the theory that decides what the physicist can observe. Einstein's discussion with Heisenberg on the day in 1926, when Heisenberg had first presented his matrix mechanics in Berlin, led Heisenberg to recognize in 1927 that it was the classical theory that led him to think that the tracks in the Wilson cloud chamber represent the movement of a particle as having a definite position and velocity that defined its trajectory. Recognition of the interpenetration of theory and observation led Heisenberg to reconsider what is observed in the cloud chamber. He then rephrased his question about trajectories in terms of the quantum theory instead of the classical theory; he asked: Can the quantum mechanics represent the fact that an electron finds itself approximately in a given place and that it moves approximately at a given velocity?

In answer to this new question he found that these approximations could be represented mathematically, and he called this mathematical representation the "uncertainty relations", also known as the "indeterminacy principle". On this principle the limit of accuracy with which both position and momentum can be known is defined in terms of Planck's constant. In the view of Heisenberg and those who advocate the "Copenhagen interpretation" this necessary degree of approximation is not merely a measurement inaccuracy, but is imposed by the nature of the universal quantum of action. Einstein's semantical principle, that theory decides what the physicist can observe, became one of the cornerstones of the post-positivist philosophy of science as articulated both by Karl Popper and by the contemporary pragmatists; it led the contemporary pragmatist philosophers to reject the positivist separation of theory and observation.

Heisenberg also describes his thought processes in this discovery experience in his chapter on the history of quantum theory in his *Physics and Philosophy* (1958). There he says that he turned around a question: instead of asking how the known formalism of Newtonian physics could be used to express a given experimental situation, he asked whether or not only such experimental situations can arise in nature as can be expressed in the mathematical formalism of his matrix mechanics. This recounting of his thinking gives greater emphasis to the ontological commitment that characterizes the "indeterminacy principle", according to which there does not simultaneously exist in reality both a determinate position and a determinate momentum for the electron. As it happens, Einstein was never willing to accept the ontology of the Copenhagen interpretation, even though Heisenberg attempted to do the same thing with his matrix mechanics that Einstein did with the Lorentz transformation, when the latter interpreted the Lorentz equation in non-Newtonian terms of actual time instead of apparent time and redefined the concept of simultaneity. Einstein maintained contrary to the Copenhagen interpretation that a more "complete" microphysical theory is needed, which would satisfy his own ontological criteria for physical reality. In imitating Einstein's reinterpretation of the Lorentz transformation, Heisenberg was practicing scientific realism, *i.e.*, ontological relativity according to which ontological commitment is extended to the most empirically adequate theory. The pragmatist philosophy of language implies this practice, in which it might be said that a *carte blanche* metaphysical realism is presumed, while the ontology describing reality is supplied by empirical science; it is a realism which is a blank check for which scientific theory specifies its cash value, and for which empirical criticism backs its negotiability.

Heisenberg did not escape the influence of positivism, even though he had departed from it in a very fundamental way to develop the indeterminacy relations. Another influence upon his thinking was Bohr's philosophy of knowledge. Bohr did not explicitly embrace positivism, but in his view classical physics is permanently valid and must serve as the language of observation, in which all accounts of evidence in physical science must be expressed. Heisenberg's attempt to reconcile the contrary influences of Einstein and Bohr resulted in his developing his semantical thesis of "closed-off theories." This is his attempt at a systematic philosophy of language for science. It is different from the logical positivist philosophy, but due to Bohr's influence it is more like positivism than the contemporary pragmatism. Einstein and Heisenberg had made very insightful criticisms of positivism, but neither produced a new systematic philosophy of language adequate to their insights in physics, however portentous these insights have turned out to be. The portended contemporary pragmatist philosophy of language and science was as great an intellectual revolution in philosophy as the revolutions in physics.

Comment and Conclusion

This chapter examined two variations on positivism formulated by two turn-of-the-twentieth-century physicists, and previewed the story of positivism's rejection by the physicists who made the two great scientific revolutions in twentieth-century physics. This latter story will be given in greater detail below in the BOOK describing Heisenberg's philosophy of quantum theory. But to appreciate these developments more adequately, it is helpful firstly to have examined the development of the pragmatist philosophy of language.

The next BOOK describes Carnap's transformation of Mach's positivism for his philosophy of semantical systems and then Quine's transformation of Duhem's positivist philosophy of mathematical physics into the contemporary pragmatism. Carnap and Quine were friends well known to one another, and both contributed insightfully to the linguistic-analysis tradition in philosophy. But Quine criticized Carnap's positivism, and elaborated Duhem's philosophy of mathematical physics beyond Carnap's positivism into a new generalized philosophy of language now known as the Duhem-Quine thesis in contemporary pragmatism.

