vaisseaux (Paris, 1759); *Des semis et plantations des arbres et de leur culture* (Paris, 1760); *Éléments d'agriculture,* 2 vols. (Paris, 1762); *Histoire d'un insecte qui dévore les grains dans l'Angoumois* (Paris, 1762); *De l'exploitation des bois,* 2 vols. (Paris, 1764); *Du transport, de la conservation et de la force des bois* (Paris, 1767); *Traité des arbres fruitiers,* 2 vols. (Paris, 1768); *Traité général des peches, et histoire des poissons qu'elles fournissent,* 3 vols. (Paris, 1769-1777). There are various translations in English, German, Spanish, and Italian.

II. SECONDARY LITERATURE. Most biographies rely heavily on the *éloge* by Condorcet in the *Histoire de l'Académie royale des sciences . . . 1782* (1785), 131-155.

Other material may be found in *Biographie universelle, ancienne et moderne,* XII (Paris, 1814), 185-190; *Dictionnaire de biographie française* (Paris, 1968), p. 22; *Dictionnaire historique de la médecine, ancienne et moderne,* II, pt. 1 (Paris, 1834), 147-149; *Dictionnaire des sciences médicales,* III (Paris, 1821), 538-541; *Nouvelle biographie générale,* XV (Paris, 1868), 106-107.

JON EKLUND

DUHEM, PIERRE-MAURICE-MARIE (*b.* Paris, France, 10 June 1861; *d.* Cabrespine, France, 14 September 1916), *physics, rational mechanics, physical chemistry, history of science, philosophy of science.*

Duhem was that rare, not to say unique, scientist whose contributions to the philosophy of science, the historiography of science, and science itself (in thermodynamics, hydrodynamics, elasticity, and physical chemistry) were of profound importance on a fully professional level in all three disciplines. Much of the purely scientific work was forgotten until recently. His apparent versatility was animated by a single-mindedness about the nature of scientific theories that was compatible with a rigidly ultra-Catholic point of view, an outlook unusual among historians, philosophers, or practitioners of science—Cauchy is the only other example that comes to mind.

Duhem's historical work, the major part of which traces the development of cosmology from antiquity to the Renaissance, was meant partly to redeem the centuries of Scholasticism, the great age for his church, from the reputation of scientific nullity, but mainly to exemplify the central epistemological position of his philosophy. This assigned to scientific theories the role of economizers of experimental laws which approach asymptotically some sort of reality, rather than that of models of reality itself or bearers of truth. Thus would the truth be independent of science and reserved for theology. This position coincided in important, although not all, respects with that of contemporary positivists, who came to it from the other extreme ideologically and without concern for defending theology.

Among the areas of agreement between Duhem, Ernst Mach, and Wilhelm Ostwald was a common predilection for the energeticist over the mechanistic position in physics itself, involving skepticism about the reality of known physical entities, although he differed from them in allowing the existence of real entities in principle, however unknowable. A similar skeptical view was held by Henri Poincaré.

Duhem's father, Pierre-Joseph, was a commercial traveler from Roubaix in the industrialized north of France. His mother, born Alexandrine Fabre, was of a bourgeois family originally from Cabrespine, a town in Languedoc, near Carcassonne. They settled in Paris and sent Duhem, the eldest of their four children, to the Collège Stanislas from his eleventh year. He was a brilliant student and there acquired the firm grasp of Latin and Greek that he would need in his historical scholarship, while being attracted primarily to scientific studies and especially thermodynamics by a gifted teacher, Jules Moutier. His father hoped that for his higher education he would enter the École Polytechnique, where the training and tradition assured most graduates eminent technical careers in the service of the state. His mother, on the other hand, fearful that science or engineering would diminish his religious faith, urged him to study humanities at the École Normale Supérieure. Having placed first in the entrance examinations, he chose the middle ground of science at the École Normale, indicating his desire for an academic career. He published his first paper, on the application of the thermodynamic potential to electrochemical cells, in 1884, while still a student.

He proceeded with distinction through the *licence* and *agrégation,* after meeting a setback with a thesis for the doctorate that he presented in 1884 (prior to receiving the *licence,* an uncommon event). The subject concerned the concept of thermodynamic potential in chemistry and physics, and the argument included an attack on Marcellin Berthelot's twenty-year-old principle of maximum work, whereby the heat of reaction defines the criterion for the spontaneity of chemical reactions. This principle is false. Duhem, following J. W. Gibbs and Hermann von Helmholtz, properly defined the criterion in terms of free energy. Berthelot was extremely influential, resented the neophyte challenge, and was able to get the thesis refused. At risk to his career, Duhem later published the thesis as a book, *Le potentiel thermodynamique* (1886). Duhem was placed under the necessity of preparing another subject for the doctorate. He received the degree in 1888 for a thesis on the theory of magnetism, this one falling within the area of mathematics.

Unfortunately the enmity between Berthelot and Duhem was not dissipated until after 1900. Moreover, Duhem was of a contentious and acrimonious disposition, with a talent for making personal enemies over scientific matters. He blamed Berthelot, who was minister of education from 1886 to 1887, together with the circle of liberal and free-thinking scientists who advised successive ministers, for preventing him from ever receiving the expected call to a professorship in Paris. Aside from the hearsay evidence of anecdotes from the personalities involved, it must be admitted that there is no other instance in modern French history of a scientist of equivalent productivity, depth, and originality remaining relegated to the provinces throughout his entire postdoctoral career. Duhem taught at Lille (1887–1893), Rennes (1893–1894), and Bordeaux (1894–1916). He spurned an offer of a professorship in the history of science at the Collège de France shortly before his death, on the grounds that he was a physicist and would not enter Paris by the back door of history. In 1900 he was elected to corresponding membership in the Academy of Sciences. In 1913 he was elected one of the first six nonresident members of the Academy, a recognition that, together with various honorary degrees and foreign academic memberships received earlier, mollified his feelings to some degree.

Duhem had few qualified students, but those he did have considered him an extraordinary teacher. His personal friendships were as warm as his professional enmities were bitter. In October 1890 while at Lille he married Adèle Chayet. She died only two years later while giving birth to their second daughter, who also died. Duhem made his home thereafter with the surviving daughter, Hélène. She saw to the publication of the final five volumes (1954–1959) of his historical masterpiece, *Le système du monde,* left in manuscript after his death. He died at fifty-five of a heart attack brought on by a walking expedition during vacation days at Cabrespine. His health had never been vigorous.

Duhem's interests fell roughly into periods. Thermodynamics and electromagnetism predominated between 1884 and 1900, although he returned to them in 1913–1916. He concentrated on hydrodynamics from 1900 to 1906. His interest in the philosophy of science was mostly in the period 1892–1906, and in the history of science from 1904 to 1916, although his earliest historical papers date from 1895. The extraordinary volume of Duhem's production is impressive—nearly 400 papers and some twenty-two books. Among them, certain wartime writings (*La science allemande* and *La chimie est-elle une science française?*) express, as do his philosophical judgments of the style of British science, a certain chauvinism that remains the only unattractive characteristic of his nonscientific writings. It will be best to consider his most important work in the order of philosophy, history, and physics; to do so will reverse its chronology but will respect its intellectual structure.

Philosophy of Science. Duhem published his major philosophical work, *La théorie physique, son objet et sa structure,* in 1906, after having largely completed his researches in physical science. "A physical theory," he held there, ". . . is a system of mathematical propositions, deduced from a small number of principles, which has the object of representing a set of experimental laws as simply, as completely, and as exactly as possible." In adopting this position, he was explicitly rejecting what he considered to be the two alternatives to which any serious existing or previous account might be reduced.

According to epistemologies of the first sort, proper physical theories have the aim of accounting for observed phenomena by proposing hypotheses about, and preferably by actually revealing, the nature of the ultimate entities underlying the phenomena in question. Duhem rejected this view as illusory because experience showed that acting upon it had had the effect historically of subordinating theoretical physics to metaphysics, thereby encumbering and distracting it with all the difficulties and disputes afflicting that subject. He allowed that physicists may appropriately hope to form theories of which the structure "reflects" reality. It may be thought of such theories that their mode of interrelating empirical laws somehow fits the way in which the real events that give rise to the observations are interrelated. This hope can be based only on faith, however. There is and can be no evidence to support it.

Little in Duhem's philosophical writings clarifies the idea of such a fit, beyond the notion that the evolution of physical theories caused by successive adjustments to conform to experiment should lead asymptotically to a "natural classification" which somehow reflects reality. But his historical writings allude to numerous examples of what he had in mind, and his *Notice* (1913) indicates that they were in part originally motivated by it. It is no doubt for this reason that, despite his enthusiastic discovery of Scholastic mechanics in the Middle Ages, his favorite philosopher of antiquity was Plato, to whom he attributed the origin of the view (clearly akin to his own) that the healthy role of astronomical or other mathematical theory is to "save the phenomena." At the same time he had great faith in the syllogism as a logical instrument. He believed that mathematical reasoning could in principle be replaced with syllogistic reasoning, and he went so far as to reject Poincaré's argument that mathematical induction involves nonsyllogistic elements.[1]

The second category of philosophies or methodologies of physics that Duhem found unacceptable were those in which theories were expected to provide models in the form of mechanical analogies or constructs that permit visualizing the phenomena and offer handles for thought. He rejected this alternative partly on utilitarian and partly on aesthetic grounds. He felt that physical theories should have practical value, and he preferred the analytic to the geometric mode in mathematical thinking. Theories of the kind he advocated permit deducing many laws from a few principles and thus dispense the physicist from the necessity of trying to remember all the laws. Duhem evidently considered reason a higher faculty than memory. Complex models are distracting to people who can reason but cannot remember a mass of concrete detail. They are not, he believed, likely to lead to discovery of new laws. Merely artificial constructs, they can never attain to the status of natural classifications. Duhem was highly critical of British physics for its reliance upon the use of just such mechanistic models. In his view this national habit resulted from a defect of cultural temperament. He described the British mind in science as wide and shallow, the French as narrow and deep. As will appear in the discussion of his electrodynamics, Maxwell was his bête noire in this respect. It must be acknowledged that a certain rigidity in his opinions accorded ill with the subtle nature of his philosophy.

Duhem's philosophy was certainly empiricist but never naïvely so. He showed very beautifully that there can be no such thing as simply observing and reporting an experiment. The phenomenon observed must be construed—must be seen—in the light of some theory and must be described in the terms of that theory. Laws arrived at experimentally must be expressed by means of abstract concepts that allow them to be formulated mathematically and incorporated in a theory. At their best they can merely approximate experimental observations. It is quite impossible to test or verify the fundamental hypotheses of a theory one by one. Thus there cannot be a crucial experiment, and induction from laws can never determine a unique set of hypotheses. Thus data and logic leave much to the discretion of the theorist. He must supplement their resources with good sense and historical perspective on his problems and his science.

It is an aspect of Duhem's recognition of the role of taste in scientific research that he never insisted that his philosophy require the adoption of an energeticist, to the exclusion of a mechanistic, point of view. That was an empirical, not a philosophical, issue. What his philosophy purported to establish was that an energeticist approach was no less legitimate than a mechanistic one. The discussion explains how theories are to be judged and looked at merely in point of preference or policy; and in the absence of concrete facts, either type of theory would in principle be acceptable, so long as no metaphysical import be loaded into the choice. The issue was one that Duhem discussed in *L'évolution de la mécanique* (1902) and also in the essay "Physique de croyant," included in later editions of *La théorie physique.*

History of Science. Like Ernst Mach, his contemporary in the positivist school, Duhem relied heavily on historical examples in presenting his philosophy of science. *L'évolution de la mécanique* may be compared to Mach's famous *Die Mechanik in ihrer Entwicklung, historisch-kritisch dargestellt* (1883) as a philosophical critique of a science based upon its history, although Duhem was by far the more faithful to the original texts and the intentions of their authors. A history of the concept of chemical combination appeared in 1902 and a two-volume study of early statics in 1905–1906.

The object of historical examples was to attempt to see the trend toward the "natural classification," which requires the examination of preceding theories. Duhem was primarily led into his historical studies by following such theories backwards. Thus he always claimed that his conception of physical theory was justified by the history of physics, not because it corresponded to views shared by all, or most, or even (as Mach had tended to imply of his own position) by the best physicists, but because it did yield an analysis of the nature of the evolution of physics and of the dialectic responsible for that process.

The most impressive monument to the scholarly fertility of that claim remains his massive contribution to the knowledge of medieval science in his three-volume *Études sur Léonard de Vinci* (1906–1913) and the ten-volume *Système du monde* (1913–1959). These works contain a detailed exposition of two theses: (1) a creative and unbroken tradition of physics, cosmology, and natural philosophy was carried on in the Latin West from about 1200 to the Renaissance, and (2) the results of this medieval activity were known to Leonardo da Vinci and Galileo, and played a seminal role in the latter's transformation of physics. Duhem was led to his theses, and to the almost single-handed discovery of this medieval activity, by recognizing in Leonardo's notebooks statements by earlier writers and references to works fortunately available in manuscript in the Bibliothèque Nationale. Pursuing these citations and references still further he found wholly unsuspected "schools of science." He emphasized the significance of Paris: particularly important was a series of Parisian masters who were relatively unknown before Duhem's researches—Jordanus de Nemore, Jean Buridan, Francis of Méyronnes, Albert of Saxony, and Nicole Oresme. Duhem also brought out of obscurity the contributions of Mersenne and Malebranche. Expressed in dramatic form and supported by extensive quotation from the original texts (particularly in *Le système du monde*), Duhem's discoveries revolutionized, if they did not completely create, the study of medieval physics. While it is true that recent studies have seriously modified and qualified some of his conclusions, Duhem's studies remain the indisputable starting point for the study of medieval natural philosophy.[2]

Scientific Thought and Work. It must be recalled that Duhem's scientific formation took place in the period 1880–1890, well before the discovery of radioactivity and the experiments of Jean Perrin and, later, Henry G. F. Moseley. Discontent with the notion of reducing all physical concepts to classical mechanics or to mechanical models was growing. It was fed by the necessity to modify ad hoc the often contradictory properties of supposedly fundamental atomic or molecular particles in order to maintain the applicability of the model to newly determined phenomena, particularly in chemical dynamics and in the physics of heat and gases. Duhem early became convinced that rather than try to reduce all of physics and chemistry to classical mechanics, the wiser policy would be to see classical mechanics itself as a special case of a more general continuum theory. He believed that such underlying descriptive theory for all of physics and chemistry would emerge from a generalized thermodynamics. The central commitment of his scientific life was the building up of such a science, one that would include electricity and magnetism as well as mechanics. His attempts culminated in the *Traité d'énergétique* (1911), in which valuable work there is not a single word about atoms or molecules. Duhem always considered that it was his most important—and would prove to be his most lasting—contribution to science. He had not succeeded, however, in his goal of including electricity and magnetism in its purview.

His conception of the nature of physical theory had in fact influenced both the direction of his work and the form of his writings. His contemporaries (see Secondary Literature) often remarked that many of his papers opened with the barest of assumptions followed by a series of theorems. In his mode of posing "axioms," he gave little motivation, made hardly any appeal to experiment, and of course made no use whatever of atomic or molecular models. In his concern over extracting the logical consequences of a set of axioms for a portion of physics or chemistry, Duhem was a pioneer. Today a flourishing school of continuum mechanics follows a similar path, with a strong interest in foundations and in finding general theorems about more general fluids or elastic bodies with nonlinear constitutive equations or with fading memory. They often cite Duhem and his more famous predecessors such as Euler and Cauchy. However, because of the special hypotheses and restricted constitutive equations built into Duhem's thermodynamics from the beginning, modern workers no longer view his generalized thermodynamics as the best way to approach continuum mechanics.[3,4]

Duhem began his scientific work with the generalization and application of thermodynamics. While still at the Collège Stanislas and under Moutier's guidance, he had read G. Lemoine's description of J. W. Gibbs's work[5] and the first part of Hermann von Helmholtz' "Die Thermodynamik chemischer Vorgänge."[6] These papers emphasized the characteristic functions, closely related to those invented by F. J. D. Massieu,[7] now called the Gibbs and Helmholtz free energies—G and A, respectively. These functions play a role for thermodynamics directly analogous to the one played by the potential of classical mechanics. Duhem was one of the first to see real promise in this, calling Massieu's functions "thermodynamic potentials." Using this idea together with the principle of virtual work, he treated a number of topics in physics and chemistry.

Among the subjects treated systematically were thermoelectricity, pyroelectricity, capillarity and surface tension, mixtures of perfect gases, mixtures of liquids, heats of solution and dilution, saturated vapors, solutions in gravitational and magnetic fields, osmotic pressure, freezing points, dissociation, continuity between liquid and gas states, stability of equilibrium, and the generalization of Le Chatelier's principle. The Duhem-Margules equation was first obtained by Duhem in the course of this work. His success with these problems in the period 1884–1900 rank him with J. H. van't Hoff, Ostwald, Svante Arrhenius, and Henry Le Chatelier as one of the founders of modern physical chemistry.

Duhem's results are of course an extension and elaboration of the pioneer work of Gibbs and Helmholtz. But Duhem's elaboration, explanation, and application of their suggestions in his *Traité de mécanique chimique* (1897–1899) and *Thermodynamique et chimie* (1902) provided a whole generation of French physicists and chemists with their knowledge of chemical thermodynamics.

Duhem made a number of other contributions to thermodynamics. In the first part of his rejected thesis, *Le potentiel thermodynamique* (1886), Duhem presented or rederived by means of the thermodynamic potential a number of known results on vapor pressure of pure liquids and solutions, dissociation of gases and of heterogeneous systems, and the heat effects in voltaic cells. In the second and third parts he obtained new results on solubility and freezing points of complex salt solutions and on electrified systems. There is also the first application of Euler's homogeneous-function theorem to the extensive properties of solutions. This technique, now common, reduces the derivation of relations among the partial molal properties of a solution to the repeated application of this theorem. One of the equations so derived is the Gibbs-Duhem equation. Also included is a discussion of electrified systems which contains an expression equivalent to the electrochemical potential. This book, popular enough to be reprinted in 1896, is historically important for the systematic use of thermodynamic potentials, when others were still using osmotic pressure as a measure of chemical affinity and using artificial cycles to prove theorems.

Duhem was the first (1887) to publish a critical analysis[8] of Gibbs's "Equilibrium of Heterogeneous Substances."[9] In Duhem's paper is the first precise definition of a reversible process; earlier versions by others (unfortunately often preserved in today's textbooks) are too vague. Duhem emphasizes that the reversible process between two thermodynamic states *A* and *B* of a system is an unrealizable limiting process. The limit of the set of real processes for getting from *A* to *B* is obtained by letting the imbalance of forces between the system and the surroundings at each step tend toward zero. Each member of this set of real processes must pass through nonequilibrium states, or else nothing would happen. However, the limit of this set, where the forces balance at every step, is a set of equilibrium states. Since once the system is in equilibrium nothing can happen, this limit is thus in principle an unrealizable process. This limiting process is now called a "quasi-static" process. If a similar set of realizable processes for getting from *B* and *A* has the same (unrealizable) limit, then the common sequence of equilibrium states is defined by Duhem as a reversible process.

Duhem later pointed out in the "Commentaire aux principes de la thermodynamique" (pt. 2, 1893) that there exist situations such as hysteresis where the limiting set of equilibrium states for the direction *AB* is not the same as that for the direction *BA*. Therefore, it is possible to go from *A* to *B* and back by quasi-static processes, but not reversibly. This distinction was noted fifteen years before the celebrated paper of Carathéodory.[10]

Duhem believed that the "Commentaire" (1892–1894) was one of his more significant contributions. It contains a very detailed analysis of the steps leading from the statement of the second law of thermodynamics to the definitions of entropy and thermodynamic potential. It also contains an axiomatic treatment of the first law of thermodynamics which is surprisingly good by present-day standards. (A different version is given in the *Traité d'énergétique* [1911].) The concepts of *oeuvre* (total energy including kinetic energy) and *travail* (work) are taken as undefined ideas. Axioms about *oeuvre* include independence of path, additivity along a path, commutativity, associativity, conservation, plus other matters often left implicit. Important to note is that the concept "quantity of heat" was not assumed but was defined in terms of energy and work. Consequently the definition, although more diffusely stated, was equivalent to and preceded that of C. Carathéodory (1909)[10] and Max Born (1921),[11] and should be called Duhem's definition. Duhem's axiomatic outlook which characterized this discussion of the first law was indeed pioneering for physics and to some extent anticipated the major axiomatic research in mathematics. Thus, although the axiomatization of arithmetic began in the first half of the nineteenth century, the research for axiomatic foundations for other branches of mathematics (Euclidean geometry, fields, groups, Boolean algebra) did not begin in earnest until 1897–1900.

In "Sur les déformations permanentes et l'hystérésis" (1896–1902), Duhem considered in some detail the thermodynamics of nonreversible but quasi-static processes and some irreversible processes, including hysteresis and creep. The results were mostly qualitative, not entirely satisfactory, and of little influence. As of this writing there is no really adequate thermodynamic theory of such systems, although interest in this subject has recently been revived.

Duhem provided the first explicit unrestricted proof of the Gibbs phase rule, based on Gibbs's suggestions, in "On the General Problem of Chemical Statics" (1898). At the same time he extended it beyond the consideration of just the intensive variables, giving the conditions necessary to specify the masses of the phases as well. The conditions are different for the pairs of variables pressure–temperature and volume–temperature, and their statement is called Duhem's theorem.[12] In addition the properties of "indifferent" systems, of which azeotropes are a simple special case, were discussed in some detail.

Duhem attached great importance to his thermodynamics of false equilibrium and friction.[13] According to Duhem, false equilibria can be divided into two classes: *apparent,* as for example a supersaturated solution, which, as a result of a small perturbation, returns instantly to thermodynamic equilibrium; and *real,* as for example organic compounds, such as diamond or petroleum constituents. Such compounds are unstable thermodynamically with respect to other substances but have remained unchanged for large perturbations throughout geological periods of time. Yet they will transform into the stable products if the perturbations are large enough (diamond to graphite by heating). A similar view was held by Gibbs (his passive resistances). The false equilibrium viewpoint was very useful to E. Jouguet, a major contributor to explosives theory and one of Duhem's disciples.[14] However, real false equilibria can also be considered as instances of extremely slow reaction rates. A violent polemic over this issue took place between 1896 and 1910. Most, but by no means all, of those interested in such questions today prefer the infinitely slow reaction rate view. Since the results are the same from either view, the choice is a personal one.

A major portion of Duhem's interest was focused on hydrodynamics and elasticity. His second book, *Hydrodynamique, élasticité, acoustique* (1891), had an important influence on mathematicians and physicists because it called attention to Hugoniot's work on waves. Jacques Hadamard, a colleague for one year and lifelong friend, remarked that this book and later conversations with Duhem led him into a major portion of his own work in wave propagation, Huygens' principle, calculus of variations, and hyperbolic differential equations. Duhem was both a pioneer and almost alone for years in trying to prove rigorous general theorems for Navier-Stokes fluids and for finite elasticity in Kelvin-Kirchhoff-Neumann bodies. His results are important and of sufficient interest later that his *Recherches sur l'hydrodynamique* (1903–1904) was reprinted in 1961.

In hydrodynamics Duhem was the first to study wave propagation in viscous, compressible, heat-conducting fluids using stability conditions and the full resources of thermodynamics (*Recherches sur l'hydrodynamique*). He showed the then startling result that no true shock waves (i.e., discontinuities of density and velocity) or higher order discontinuities can be propagated through a viscous fluid. This is contrary to the result for rigorously nonviscous fluids. The only discontinuities that can persist are transversal, which always separate the same particles; these Duhem identified with the "cells," observed by Bénard, formed when a liquid is heated from below. Since real fluids are both viscous and heat conducting, how is it possible to have sound waves propagated, as in air? Duhem's answer was that while true waves are not possible, "quasi waves" are. A quasi wave is a thin layer whose properties, including velocity, change smoothly but rapidly. If we consider a series of similar fluids whose values of the heat conductivity k and viscosity η approach zero, then the thickness of the associated quasi wave also approaches zero and the smooth change of properties approaches a discontinuity. When k and η are small, as in air, such quasi waves behave exactly as a true longitudinal shock wave in a perfect fluid with $k = \eta = 0$, i.e, propagating with the Laplace velocity. Duhem's concept and theory of the quasi wave is more general and more precise than the later ideas of Prandtl (1906) about the "shock layer." Some of Duhem's theorems on shock waves have been improved recently. For perspective, it should also be noted that Duhem considered only the then universally accepted Navier-Stokes fluid. There are more general concepts of a fluid with viscosity which do allow wave propagation.[4]

Duhem generalized and completed earlier results on the stability of floating bodies (including those containing a liquid). He showed that while some earlier methods were incorrect, certain results (in particular the famous rule of metacenters) were still correct. Finally, the article "Potentiel thermodynamique et pression hydrostatique" (1893) contains, but does not develop, the idea of an oriented body that consists not only of points but of directions associated with the points. Such an oriented body can represent liquid crystals or materials whose molecules have internal structure. Eugène and François Cosserat adapted this idea to represent the twisting of rods and shells in one and two dimensions (1907–1909). This concept has also been useful for some recent theories of bodies with "dislocations."

In elasticity Duhem was again interested in rigorous general theorems (*Recherches sur l'élasticité* [1906]). He kept a correct finite elasticity alive and inspired other workers. He was the first to study waves in elastic, heat-conducting, viscous, finitely deformed systems. The results are similar to that for fluids; namely, in any finitely deformed viscous elastic system, whether crystalline or vitreous, no true waves can be propagated and the only possible discontinuities always separate the same particles (as in the Bénard problem). Quasi waves are expected in viscous solids, but Duhem did not carry his analysis that far. Duhem was also the first to study the relationships between waves in isothermal (heat-conducting) and adiabatic (nonconducting) finitely deformed systems without viscosity. Duhem was also interested in the general conditions for solids (vitreous or crystalline) to be stable. He had to choose special conditions of stress or strain, but he was able to prove some general theorems. All this was based on the then universally accepted Kelvin-Kirchhoff-

Neumann elastic body. At the present writing, more general concepts of elastic bodies are being considered.

After Gibbs, Duhem was among the few who were concerned about stability of thermodynamic systems. His techniques were a natural consequence of his interest in thermodynamic potentials. He was the first to consider solutions ("Dissolutions et mélanges" [1893]); and he often returned to stability questions ("Commentaire aux principes de la thermodynamique" [1894]; "On the General Problem of Chemical Statics" [1898]; *Recherches sur l'élasticité* [1906]; *Traité d'énergétique* [1911]). Because he tried to be more explicit and more general than Gibbs and because he often took a global point of view, he had to face more difficult problems than did Gibbs. He succeeded fairly well with sufficient conditions but was less successful with necessary ones. In his *Énergétique* he showed familiarity with Liapounoff's work, but his own previous results were based on more special hypotheses. As a result, there is some confusion in Duhem's results over what are the proper necessary and sufficient conditions for thermodynamic stability. Such questions have only recently been rigorously resolved.

Electricity and magnetism and his attempts to bring them into the framework of his *Énergétique* (which was not the same as the philosophical school of "energetics") were important to Duhem. If a system's currents are zero or constant, then its electrodynamic energy is zero or constant. In this case, the total energy divides neatly into internal and kinetic energies, and energetics can be successfully applied. Thus Duhem was able to treat pyroelectricity and piezoelectricity in a general way without needing the special hypotheses of F. Pockels and W. Voigt. However, if currents are not constant, then matters are much more complex, and the electrodynamic energy must be accounted for using some electromagnetic theory.

Although Duhem recognized J. Clerk Maxwell's ingenuity, he could not appreciate Maxwell's theory at its real value because of its contradictions and unrigorous development, its mistakes in sign, and its lack of experimental foundation. Duhem preferred an electromagnetic theory due to Helmholtz, since it could be logically derived from the classical experiments. This theory, which Duhem helped to elaborate—and improve—is more general than Maxwell's because it contains two additional arbitrary parameters. By an appropriate choice of values for these parameters, it can be shown that Maxwell's equations appear as special cases of Helmholtz' theory. In particular, if the Faraday-Mossotti hypothesis is adopted (equivalent to one parameter being infinity), then transverse fluxes propagate with the velocity of light. This results in an electromagnetic theory of light and an explanation of Heinrich Hertz's experiments. If the other parameter (Helmholtz') is chosen to be zero, then no longitudinal fluxes can be propagated, which circumstance is in agreement with Maxwell's equations. Duhem, however, believed that there were experiments showing that such longitudinal fluxes exist and are also propagated at the velocity of light. He suggested (1902) that perhaps the recently discovered X rays might be identified with these longitudinal fluxes.

Duhem was a pitiless critic of Maxwell's theory, claiming that it not only lacked rigorous foundation but was not sufficiently general to explain the existence of permanent magnets (*Les théories électriques de J. Clerk Maxwell* [1902]). Similar reservations about lack of rigor were expressed by many Continental physicists (e.g., Poincaré), and Helmholtz worked out his own electromagnetic theory because of his dissatisfaction with Maxwell's approach. Duhem later admitted that not only had his criticisms not been accepted, they had not even been read or discussed; and of course Maxwell's theory has triumphed. However, both L. Roy[15] and A. O'Rahilly[16] have contended that the logical derivation of Maxwell's equations from a continuum viewpoint comes best through the Helmholtz-Duhem theory with the proper choice of constants.

The foregoing discussion covers an extraordinary output of purely scientific work. It is curious that until recently working scientists were almost completely unaware of these contributions, with the exception of the Gibbs-Duhem and Duhem-Margules equations, which have been well known to physical chemists. The reason for the neglect of Duhem's scientific work, the failure to call him to Paris, and the long delay in his election to the Academy—despite the high quality of his work and the foreign honors accorded him—are interesting and are summarized below. They involve aspects of Duhem's personality as well as differences between competing scientific schools of the period. (A more complete account of the antagonisms and suppression, interwoven with a biography, may be found in Miller, *Physics Today,* **19**, no. 12 [1966], 47–53.)

Duhem's contentious characteristics have already been noted. On the one hand, his extremely conservative religious and political views conflicted sharply with those of the freethinkers and liberals who then dominated French science. On the other hand, the polemical nature of his writings on such controversies as energetics vs. atomism, Maxwell's theory vs. Helmholtz', relativity, false equilibrium, and the maximum work principle made personal enemies of many of his scientific contemporaries. Their combined opposition blocked his career and resulted in partial suppression of his work or in its being taken over without citation.

In part, however, the neglect of his work is to be explained by the triumph of views that he bitterly opposed, such as atomic theories and Maxwell's theory. His objection to relativity derived from its "mutilation" of classical mechanics in order to leave unaltered Maxwell's theory and atomic theories of electrons.

With the crystal clarity of a half century of hindsight, it would seem that Duhem should not have opposed corpuscular models so strongly. Since he had based his whole philosophy on the deliberate avoidance of such aids and given the rigid nature of his personality, he could not change his views as the evidence mounted and the use of such models became more plausible. It is essential to recall, however, that Duhem was not alone in his objection to corpuscular models, Maxwell, and relativity. At the time he was in the company of many eminent scientists.

Pierre Duhem is a fascinating example of a brilliant scientist caught up in historical and personal circumstances that blocked his career and partially suppressed his scientific work. Right-wing, royalist, anti-Semitic, anti-Dreyfus, anti-Republican, and a religious extremist, he was exiled to the provinces and his scientific work was almost systematically ignored in France.

Nevertheless, Duhem's scientific ideas and outlook had a major influence on French physical chemistry and particularly on Hadamard, Jouguet, and the Cosserats. He was a pioneer in attempting to prove rigorous general theorems about thermodynamics, physical chemistry, Navier-Stokes fluids, finite elasticity, and wave propagation. His purely scientific investigations and results in these fields are important, useful, and significant today, although the ascendancy of atomic theories has diminished the relative importance of his contributions to science as a whole.

By midcentury Duhem's scientific work had been almost completely forgotten. Since then, his contributions have been rediscovered, and are being increasingly cited and given the recognition they deserve.[3,4,12] There has never been, of course, any question about the importance of his work in the philosophy and history of science. Since his contributions to any one of the fields of pure science, philosophy, or history would have done credit to one person, the ensemble from the pen of a single man marks Duhem as one of the most powerful intellects of his period.

NOTES

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15. L. Roy, *L'électrodynamique des milieux isotropes en repos d'après Helmholtz et Duhem* (Paris, 1923).
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I. ORIGINAL WORKS. Duhem published twenty-two books in forty-five volumes, as well as nearly 400 articles and book reviews in scientific and philosophical journals. An extensive bibliography (although lacking some twenty-five articles and more than fifty book reviews) is given by O. Manville, in *Mémoires de la Société des sciences physiques et naturelles de Bordeaux,* 7th ser., **1**, pt. 2 (1927), 437–464.

Duhem's correspondence consists of letters to him from some 500 correspondents and is being copied with the permission of Duhem's daughter, Mlle. Hélène Pierre-Duhem. Copies will ultimately be deposited in the University of California, Berkeley, and University of California, San Diego, libraries. Few letters by Duhem survive. Little of the correspondence seems to have major scientific value, although there are a few interesting historical items.

Duhem's major scientific books are *Le potentiel thermodynamique et ses applications à la mécanique chimique et à la théorie des phénomènes électriques* (Paris, 1886); *Hydrodynamique, élasticité, acoustique,* 2 vols. (Paris, 1891); *Leçons sur l'électricité et le magnétisme,* 3 vols. (Paris, 1891-1892); *Traité élémentaire de la mécanique chimique,* 4 vols. (Paris, 1897-1899); *Les théories électriques de J. Clerk Maxwell: Étude historique et critique* (Paris, 1902); *Thermodynamique et chimie* (Paris, 1902; 2nd ed., 1910), English trans. by G. Burgess (New York, 1903); *Recherches sur l'hydrodynamique,* 2 vols. (Paris, 1903-1904; repr., 1961); *Recherches sur l'élasticité* (Paris, 1906); and *Traité d'énergétique,* 2 vols. (Paris, 1911).

His major historical books are *Le mixte et la combinaison chimique. Essai sur l'évolution d'une idée* (Paris, 1902); *L'évolution de la mécanique* (Paris, 1902); *Les origines de la statique,* 2 vols. (Paris, 1905-1906); *Études sur Léonard de Vinci, ceux qu'il a lus et ceux qui l'ont lu,* 3 vols. (Paris, 1906-1913); and *Le système du monde. Histoire des doctrines cosmologiques de Platon à Copernic,* 10 vols. (Paris, 1913-1959).

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For Duhem's own assessment of his work to 1913, see *Notice sur les titres et travaux scientifiques de Pierre Duhem* (Bordeaux, 1913), prepared by him for his candidacy at the Académie des Sciences. There remains an unpublished work on capillarity written several years before his death.

II. SECONDARY LITERATURE. *Mémoires de la Société des sciences physiques et naturelles de Bordeaux,* 7th ser., **1,** pt. 2 (1927) is a special issue entitled "L'oeuvre scientifique de Pierre Duhem"; in addition to the bibliography by O. Manville, cited above, it contains Manville's detailed discussion of Duhem's physics, pp. 1-435, and shorter discussions of his mathematical work by J. Hadamard, pp. 465-495, and of his historical work by A. Darbon, pp. 497-548.

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DUJARDIN, FÉLIX (*b.* Tours, France, 5 April 1801; *d.* Rennes, France, 8 April 1860), *protozoology.*

Both Dujardin's father and grandfather were skilled watchmakers, originally in Lille, and Félix, who for a time trained in the trade, seems to have acquired some of his interests—as well as his remarkable manual dexterity—from them.

With his two brothers, Dujardin attended the classes of the Collège de Tours as a day pupil. He was originally attracted to art, especially drawing and design. His interest in science was apparently first aroused by a surgeon who was a friend of the family and who lent him some books on anatomy and natural history as well as Fourcroy's *Chimie.* Chemistry be-