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JACQUES PAYEN

AMPÈRE, ANDRÉ-MARIE (*b.* Lyons, France, 22 January 1775; *d.* Marseilles, France, 10 June 1836), *mathematics, chemistry, physics.*

Ampère's father, Jean-Jacques, was a merchant of independent means who, soon after his son's birth, moved the family to the nearby village of Poleymieux, where André-Marie grew up. The house is today a national museum. Jean-Jacques Ampère had been greatly influenced by the educational theories of Rousseau and was determined to educate his son along the lines laid down in *Émile.* The method he seems to have followed was to expose his son to a considerable library and let him educate himself as his own tastes dictated. One of the first works Ampère read was Buffon's *Histoire naturelle,* which stimulated his lifelong interest in taxonomy. Probably the most important influence on him was the great *Encyclopédie*—even thirty years later he could recite many of the articles from memory. In his father's library he also discovered Antoine Laurent Thomas's eulogy of Descartes, which convinced him of the nobility of a life in science. It also introduced him to metaphysics, the one passion he sustained throughout his life.

Almost incidentally Ampère discovered and perfected his mathematical talents. As an infant, he was fascinated by numbers and taught himself the elements of number theory. Like the young Pascal, having been forbidden the rigors of geometry because of his tender years, he defied parental authority and worked out the early books of Euclid by himself.

When the librarian in Lyons informed him that the works by Euler and Bernoulli that he wished to read were in Latin, Ampère rushed home to learn this language. He soon became adept enough to read the books that interested him, but continued his studies to the point where he could write quite acceptable Latin verse.

Ampère's early education was also conducted in a deeply religious atmosphere. His mother, the former Jeanne Desutières-Sarcey, was a devout woman who saw to it that her son was thoroughly instructed in the Catholic faith. Throughout his life, Ampère reflected the double heritage of the *Encyclopédie* and Catholicism. He was almost constantly assailed by the doubts sown by the Encyclopedists and, just as constantly, renewed his faith. From this conflict came his concern for metaphysics, which shaped his approach to science.

Ampère's childhood ended in 1789 with the outbreak of the French Revolution. Although Poleymieux was a rural backwater, the events in Lyons soon involved the Ampère family. Jean-Jacques was called upon by his fellow citizens to assume the post of *juge de paix,* a post with important police powers. He met the threat of a Jacobin purge head-on by ordering the arrest of Joseph Chalier, the leading Jacobin of Lyons. Chalier was executed. When Lyons fell to the troops of the Republic, Jean-Jacques Ampère was tried and guillotined on 23 November 1793. The event struck André-Marie like a bolt of lightning. The world had always been remote; now it had moved to the very center of his life, and this sudden confrontation was more than he could immediately bear. For a year he retreated within himself, not speaking to anyone and trying desperately to understand what had happened. His contact with the outside world was minimal; only an interest in botany, stimulated by a reading of Rousseau's letters on the subject, seemed to survive.

It was in this extremely vulnerable emotional state that Ampère met the young lady who was to become his wife. Julie Carron was somewhat older than Ampère and as a member of a good bourgeois family must have seen Ampère's suit in a somewhat unfavorable light. Although the Ampères and the Carrons lived in neighboring villages and shared a common economic and social background, marriage seemed impossible. At twenty-two, Ampère had only a small patrimony and no trade or other special skill. He was also homely and rustic, characteristics that were hardly likely to attract someone accustomed to the society and usages of Lyons. Ampère's courtship, carefully documented in his journal, reveals an essential aspect of his character: he was an incurable romantic whose emotional life was both intense and simple. Having lost his heart to Julie, he had no choice but to pursue her until she finally consented to marry him. His joy, like his despair at the death of his father, was immoderate. So, in his science, Ampère was possessed by his own enthusiasm. He never laid out a course of experiments or line of thought; there would be a brilliant flash of insight that he would pursue feverishly to its conclusion.

On 7 August 1799 Ampère and Julie were wed. The next four years were the happiest of Ampère's life. At first he was able to make a modest living as a mathematics teacher in Lyons, where on 12 August 1800 his son, Jean-Jacques, was born. In February 1802 Ampère left Lyons to become professor of physics and chemistry at the *école centrale* of Bourg-en-Bresse, a position that provided him with more money and, more important, with the opportunity to prepare himself for a post in the new *lycée* that Napoleon intended to establish at Lyons. In April of that year he began work on an original paper on probability theory that, he was convinced, would make his reputation. Thus, everything concurred to make him feel the happiest of men. Then tragedy struck. Julie had been ill since the birth of their son, and on 13 July 1803 she died. Ampère was inconsolable, and began to cast about desperately for some way to leave Lyons and all its memories.

On the strength of his paper on probability, he was named *répétiteur* in mathematics at the École Polytechnique in Paris. Again his emotional state was extreme, and again he fell victim to it. Bored by his work at the École Polytechnique, lonely in a strange and sophisticated city, Ampère sought human companionship and was drawn into a family that appeared to offer him the emotional warmth he so desperately craved. On 1 August 1806 he married Jeanne Potot. The marriage began under inauspicious circumstances: his father-in-law had swindled him out of his patrimony and his wife had indicated that she was uninterested in bearing children. The marriage was a catastrophe from the very beginning. After the birth of a daughter, Albine, his wife and mother-in-law made life so unbearable for Ampère that he realized that his only recourse was a divorce. Albine joined Jean-Jacques in Ampère's household, now presided over by his mother and his aunt, who had come to Paris from Poleymieux.

In 1808 Ampère was named inspector general of the newly formed university system, a post he held, except for a few years in the 1820's, until his death. On 28 November 1814 he was named a member of the class of mathematics in the Institut Impérial. In September 1819 he was authorized to offer a course in philosophy at the University of Paris, and in 1820 he was named assistant professor (*professeur suppléant*) of astronomy. In August 1824 Ampère was elected to the chair of experimental physics at the Collège de France.

During these years, Ampère's domestic life continued in turmoil. His son, for whom he had great hopes, fell under the spell of Mme. Recamier, one of the great beauties of the Empire, and for twenty years was content to be in her entourage. His daughter, Albine, married an army officer who turned out to be a drunkard and a near maniac. There was, too, a constant anxiety about money. In 1836 Ampère's health failed and he died, alone, while on an inspection tour in Marseilles.

Ampère's personal misery had an important effect on his intellectual development. His deep religious faith was undoubtedly strengthened by the almost constant series of catastrophes with which he was afflicted. Each successive tragedy also reinforced his desire for absolute certainty in some area of his life. His son later remarked on this characteristic of his father's approach; he was never content with probabilities but always sought Truth. It is no coincidence that his first mathematical paper, "Des considérations sur la théorie mathématique du jeu" (1802), proved that a single player inevitably would lose in a game of chance if he were opposed by a group whose financial resources were infinitely larger than his own. The outcome was certain.

In science Ampère's search for certainty and the exigencies of his faith led him to devise a philosophy that determined the form of his scientific research. The dominant philosophy in France in the early years of the nineteenth century was that of the Abbé de Condillac and his disciples, dubbed *Idéologues* by Napoleon. It maintained that only sensations were real, thus leaving both God and the existence of an objective world open to doubt. Such a position was abhorrent to Ampère, and he cast about for an alternative view. He was one of the earliest Frenchmen to discover the works of Immanuel Kant. Although Kant's philosophy made it possible to retain one's religious faith, Ampère felt that his treatment of space, time, and causality implied the doubtful existence of an objective reality at a fundamental level.

Space and time, as Ampère interpreted Kant, became subjective modes of the human understanding, and Ampère, as a mathematician, could not accept this.

He therefore constructed his own philosophy. Its foundation was provided by his friend Maine de Biran, who felt he had successfully refuted David Hume's conclusion that *cause* simply meant succession of phenomena in time. The act of moving one's arm provided a firm proof that a cause explained an act and was not simply a description of succession. One wills the arm to move and one is conscious of the act of willing; the arm then moves. Therefore the arm moves *because* one wills it to. Ampère used this argument to prove the existence of an external world. If one's arm cannot move because it is, say, under a heavy table, then one becomes conscious of causes external to oneself. The arm does not move because the table prevents it from doing so. Thus Ampère carried causation from the psychological world to the physical world. Moreover, the resistance of the table proved, to Ampère's satisfaction, that matter does exist, for this external cause must be independent of our sensation of it. With similar arguments, Ampère was able to prove that the soul and God also must exist.

Ampère's philosophy permitted him to retain both a belief in God and a belief in the real existence of an objective nature. The next step was to determine what could be known about the physical world. Here again, Ampère's analysis contained highly idiosyncratic views on the nature of scientific explanation which were to be clearly illustrated in his own work. There are (and here the influence of Kant is obvious) two levels of knowledge of the external world. There are phenomena, presented to us directly through the senses, and there are noumena, the objective causes of phenomena. Noumena, according to Ampère, are known through the activity of the mind, which hypothesizes certain real, material entities whose properties can be used to account for phenomena. These two aspects of reality, however, are not all that we can know. We also can know relations (*rapports*) between phenomena and relations between noumena, and these relations are just as objectively real as the noumena. One example may suffice to illustrate this. It had been known since the end of the eighteenth century that two volumes of hydrogen combined with one volume of oxygen to form two volumes of water vapor. This is knowledge of a specific phenomenon.

In 1808 Gay-Lussac discovered that all gases combine in simple ratios, and thus was able to announce his law of combining volumes. The law states a relationship between phenomena and thereby extends our knowledge of the phenomenal world. In 1814 Ampère published his "Lettre de M. Ampère à M. le comte Berthollet sur la détermination des proportions dans lesquelles les corps se combinent d'après le nombre et la disposition respective des molécules dont leurs particules intégrantes sont composées."[1] It was an attempt to provide the noumenal, and therefore deeper, explanation of the phenomenal relations. From the theory of universal attraction used to account for the cohesion of bodies and the fact that light easily passes through transparent bodies, Ampère concluded that the attractive and repulsive forces associated with each molecule hold the ultimate molecules of bodies at distances from one another that are, as Ampère put it, "infinitely great in comparison to the dimensions of these molecules." This is knowledge of the noumena. It explains certain basic qualities of the observable world in terms of theoretical entities whose properties can be hypothesized from phenomena.

From the science of crystallography Ampère borrowed the idea of the integral particle, that is, the smallest particle of a crystal that has the form of the crystal. Ampère's molecules now were assumed to group themselves in various ways to form particles that had specific geometric forms. Thus there would be particles composed of four molecules that formed tetrahedrons (oxygen, nitrogen, and hydrogen), of six molecules that formed an octahedron (chlorine), etc. These geometrical forms were of the greatest importance in Ampère's theory, for they allowed him to deal with the problem of elective affinity and also to deduce Avogadro's law. Ampère's particles were compound and could, therefore, be broken down into smaller parts. Thus, oxygen was composed of four molecules that could, and did, separate under certain conditions, with two molecules going one way and two the other. The rule was that only compounds whose molecules were regular polyhedrons could be formed. If a tetrahedron met an octahedron, there could not be a simple combination, for the result would be a bizarre (in Ampère's terms) geometrical figure. Two tetrahedrons could combine with one octahedron, however, since the result would be a dodecahedron.

Ampère's philosophy and its influence on his science are obvious here. The relations of noumena, in this case the association of molecules to form a geometrically regular form, are simply assumed. If Ampère had been asked what evidence he had for the existence of such forms, he would have replied that no evidence could be offered. One hypothesizes noumena and relations between them in order to give causal explanations of phenomena. There can be no "evidence" for the noumena; there can be only the greater or lesser success of the noumenal hypothesis in explaining what can be observed. The point is of central importance, for it permitted Ampère to assume whatever he wished about the noumena. His assumption of an electrodynamic molecule followed this pattern exactly.

Ampère's philosophical analysis also provided him with the key for his classification of the sciences, which he considered the capstone of his career. Like Kant, he was concerned with relating precisely what man could know with the sciences that dealt with each part of man's ability to know. The chart appended to the first volume of his *Essai sur la philosophie des sciences* (1834) seems, at first glance, to be a fantastic and uncorrelated list of possible objects of investigation. If Ampère's philosophical views are attended to, however, they all fall into a rather simple pattern. We may use general physics as an example. In Ampère's classification this is divided into two second-order sciences—elementary general physics and mathematical physics. Each of these, in turn, has two divisions. Elementary general physics consists of experimental physics and chemistry; mathematical physics is divided into stereonomy and atomology (Ampère's neologisms). Experimental physics deals with phenomena, i.e., with the accurate description of physical facts. Chemistry deals with the noumenal causes of the facts discovered by experimental physics. Stereonomy concerns the relations between phenomena, e.g., laws of the conduction of heat through a solid. Atomology explains these laws by demonstrating how they may be deduced from relations between the ultimate particles of matter. All other sciences are treated in this fashion and have exactly the same kind of fourfold division.

This classification reveals Ampère's far-ranging mind and permits us to understand his occasional excursions into botany, taxonomy, and even animal anatomy and physiology. He was, in large part, seeking confirmation for his philosophical analysis, rather than setting out on new scientific paths. By the time of his death, Ampère had found, to his great satisfaction, that his scheme did fit all the sciences and, in his *Essai sur la philosophie des sciences*, he maintained that the fit was too good to be coincidence; the classification must reflect truth. Once again he had found certainty where his predecessors had not.

Although the one continuing intellectual passion of Ampère's life from 1800 to his death was his philosophical system, these years were also devoted to scientific research of considerable originality. From 1800 to about 1814, he devoted himself primarily to mathematics. As his mathematical interests declined, he became fascinated with chemistry and, from 1808 to 1815, spent his spare time in chemical investigations. From 1820 to 1827, he founded and developed the science of electrodynamics, the scientific work for which he is best known and which earned him his place in the first rank of physicists.

Ampère was not a truly outstanding mathematician. His first paper showed considerable originality and, more revealingly, great ability as an algorist. Like Leonhard Euler, Ampère had the uncanny ability, found only in the born mathematician, to discover mathematical relations. His largest mathematical memoir, "Mémoire sur l'intégration des équations aux différences partielles" (1814), was on various means of integrating partial differential equations. Although one should not underestimate the utility of such works, they should not be put in the same class as, say, the invention of quaternions by Sir William Rowan Hamilton or the laying of rigorous foundations of the calculus by Augustin Cauchy.

Ampère's failure to achieve the early promise he had shown in mathematics was undoubtedly the result of his passion for metaphysics and the necessity of earning a living. But there was also the fact, worth noting here, that the French scientific system forced him to do mathematics when his interests were focused elsewhere. Having been classified as a mathematician, Ampère found himself unable to gain recognition as anything else until after his epoch-making papers on electrodynamics. The security that came with election to the Academy of Sciences was achieved by Ampère only at the cost of putting aside his chemical interests and writing a mathematical memoir for the express purpose of gaining entry to the Academy. Original mathematical work is rarely done under such conditions.

Ampère's interest in chemistry had been aroused in the days when he gave private lessons at Lyons. This interest continued to grow at Bourg-en-Bresse, where he mastered the subject, and it became most intense about 1808, when Humphry Davy was shaking the foundations of the orthodox chemistry of the French school. Ampère once described himself as credulous in matters of science, and this again reflected his philosophy. A new scientific idea could be immediately accepted as a hypothesis even if there was no evidence for it, just as a fundamental assumption could be made without evidence: the main criterion was whether it worked or not. Ampère was not committed to Lavoisier's system of chemistry.

When Davy announced the discovery of sodium and potassium, the orthodox were startled, if not dismayed. How could oxygen be the principle of acidity, as Lavoisier had insisted, if the oxides of potassium and sodium formed the strongest alkalies?

For Ampère there was no problem; he simply accepted the fact. If this fact were true, however, then the oxygen theory of acids was probably wrong. And if this were so, then the great riddle of muriatic acid could easily be solved. The green gas that was given off when muriatic acid was decomposed need not be a compound of some unknown base and oxygen; it could be an element. Thus, at the same time that Davy was questioning the compound nature of chlorine, Ampère had also concluded that it was an element. Unfortunately, and much to his later regret, he had neither the time nor the resources to prove this point, and the credit for the discovery of chlorine as an element went to Davy. Ampère was forestalled once again by Davy in 1813, when he brought Davy a sample of a new substance that Bernard Courtois had isolated from seaweed. Ampère had already seen its similarities to chlorine, but it was Davy who first publicly insisted upon its elemental character and named it iodine.

The noumenal aspect of chemistry fascinated Ampère. Although his derivation of Avogadro's law came three years after Avogadro had enunciated it, the law is known today in France as the Avogadro-Ampère law. This was Ampère's first excursion into molecular physics, and was followed almost immediately by a second. In 1815 he published a paper demonstrating the relation between Mariotte's (Boyle's) law and the volumes and pressures of gases at the same temperature. The paper is of some interest as a pioneer effort, along with Laplace's great papers on capillarity, in the application of mathematical analysis to the molecular realm.

In 1816 Ampère turned to the phenomenal relations of chemistry in a long paper on the natural classification of elementary bodies ("Essai d'une classification naturelle pour les corps simples"). Here he drew attention to the similarities between Lavoisier's and his followers' classification of elements in terms of their reactions with oxygen and Linnaeus' classification of plants in terms of their sexual organs. Bernard de Jussieu had successfully challenged Linnaeus with his natural system that took the whole plant into account and sought affinities between all parts of the plant, not just the flowers, as the basis of classification. Ampère now wished to do the same thing for chemistry. By discovering a natural classification, i.e., one that tied the elements together by real rather than artificial relations, Ampère hoped to provide a new insight into chemical reactions. His classificatory scheme, therefore, was not merely an ordering of the elements but, like the later periodic table of Dmitri Mendeleev, a true instrument of chemical research. Unfortunately, Ampère's system was as artificial as Lavoisier's. Although he looked for more analogies among elements than Lavoisier had, the ones he selected offered little insight into the relations between the groups founded on them. The paper may be noted, however, as an early attempt to find relationships between the elements that would bring some order into the constantly growing number of elementary bodies.

By 1820 Ampère had achieved a certain reputation as both a mathematician and a somewhat heterodox chemist. Had he died before September of that year, he would be a minor figure in the history of science. It was the discovery of electromagnetism by Hans Christian Oersted in the spring of 1820 which opened up a whole new world to Ampère and gave him the opportunity to show the full power of his method of discovery. On 4 September 1820 François Arago reported Oersted's discovery to an astonished and skeptical meeting of the Académie des Sciences. Most of the members literally could not believe their ears; had not the great Coulomb proved to everyone's satisfaction in the 1780's that there could not be any interaction between electricity and magnetism? Ampère's credulity served him well here; he immediately accepted Oersted's discovery and turned his mind to it. On 18 September he read his first paper on the subject to the Académie; on 25 September and 9 October he continued the account of his discoveries. In these feverish weeks the science of electrodynamics was born.

There is some confusion over the precise nature of Ampère's first discovery. In the published memoir, "Mémoire sur l'action naturelle de deux courants électriques . . ." (1820), he stated that his mind leaped immediately from the existence of electromagnetism to the idea that currents traveling in circles through helices would act like magnets. This may have been suggested to him by consideration of terrestrial magnetism, in which circular currents seemed obvious. Ampère immediately applied his theory to the magnetism of the earth, and the genesis of electrodynamics may, indeed, have been as Ampère stated it. On the other hand, there is an account of the meetings of the Académie des Sciences at which Ampère spoke of his discoveries and presented a somewhat different order of discovery. It would appear that Oersted's discovery suggested to Ampère that two current-carrying wires might affect one another. It was this discovery that he announced to the Académie on 25 September.[2] Since the pattern of magnetic force around a current-carrying wire was circular, it was no great step for Ampère the geometer to visualize the resultant force if the wire were coiled into a helix. The mutual attraction and repulsion of two helices was also announced to the Académie on 25 September. What Ampère had done was to present a new theory of magnetism as electricity in motion.

From this point on, Ampère's researches followed three different but constantly intertwining paths. They conform exactly to his ideas on the nature of science and scientific explanation. The phenomenon of electromagnetism had been announced by Oersted; the relations of two current-carrying wires had been discovered by Ampère. It remained to explore these relations in complete and elaborate detail. Then, following his own philosophy, it was necessary for Ampère to seek the noumenal causes of the phenomena, which were found in his famous electrodynamic model and theory of the nature of electricity. Finally, Ampère had to discover the relations between the noumena from which all the phenomena could be deduced. Between 1820 and 1825 he successfully completed each of these tasks.

Ampère's first great memoir on electrodynamics was almost completely phenomenological, in his sense of the term. In a series of classical and simple experiments, he provided the factual evidence for his contention that magnetism was electricity in motion. He concluded his memoir with nine points that bear repetition here, since they sum up his early work.

> 1. Two electric currents attract one another when they move parallel to one another in the same direction; they repel one another when they move parallel but in opposite directions.
>
> 2. It follows that when the metallic wires through which they pass can turn only in parallel planes, each of the two currents tends to swing the other into a position parallel to it and pointing in the same direction.
>
> 3. These attractions and repulsions are absolutely different from the attractions and repulsions of ordinary [static] electricity.
>
> 4. All the phenomena presented by the mutual action of an electric current and a magnet discovered by M. Oersted . . . are covered by the law of attraction and of repulsion of two electric currents that has just been enunciated, if one admits that a magnet is only a collection of electric currents produced by the action of the particles of steel upon one another analogous to that of the elements of a voltaic pile, and which exist in planes perpendicular to the line which joins the two poles of the magnet.
>
> 5. When a magnet is in the position that it tends to take by the action of the terrestrial globe, these currents move in a sense opposite to the apparent motion of the sun; when one places the magnet in the opposite position so that the poles directed toward the poles of the earth are the same [S to S and N to N, not south-seeking to S, etc.] the same currents are found in the same direction as the apparent motion of the sun.
>
> 6. The known observed effects of the action of two magnets on one another obey the same law.
>
> 7. The same is true of the force that the terrestrial globe exerts on a magnet, if one admits electric currents in planes perpendicular to the direction of the declination needle, moving from east to west, above this direction.
>
> 8. There is nothing more in one pole of a magnet than in the other; the sole difference between them is that one is to the left and the other is to the right of the electric currents which give the magnetic properties to the steel.
>
> 9. Although Volta has proven that the two electricities, positive and negative, of the two ends of the pile attract and repel one another according to the same laws as the two electricities produced by means known before him, he has not by that demonstrated completely the identity of the fluids made manifest by the pile and by friction; this identity was proven, as much as a physical truth can be proven, when he showed that two bodies, one electrified by the contact of [two] metals, and the other by friction, acted upon each other in all circumstances as though both had been electrified by the pile or by the common electric machine [electrostatic generator]. The same kind of proof is applicable here to the identity of attractions and repulsions of electric currents and magnets.[3]

Here Ampère only hinted at the noumenal background. Like most Continental physicists, he felt that electrical phenomena could be explained only by two fluids and, as he pointed out in the paper, a current therefore had to consist of the positive fluid going in one direction and the negative fluid going in the other through the wire. His experiments had proved to him that this contrary motion of the two electrical fluids led to unique forces of attraction and repulsion in current-carrying wires, and his first paper was intended to describe these forces in qualitative terms. There was one problem: how could this explanation be extended to permanent magnets? The answer appeared deceptively simple: if magnetism were only electricity in motion, then there must be currents of electricity in ordinary bar magnets.

Once again Ampère's extraordinary willingness to frame *ad hoc* hypotheses is evident. Volta had suggested that the contact of two dissimilar metals would give rise to a current if the metals were connected by a fluid conductor. Ampère simply assumed that the contact of the molecules of iron in a bar magnet would give rise to a similar current. A magnet could, therefore, be viewed as a series of voltaic piles in which electrical currents moved concentrically around the axis of the magnet. Almost immediately, Ampère's friend Augustin Fresnel, the creator of the wave theory of light, pointed out that this hypothesis simply would not do. Iron was not a very good conductor of the electrical fluids and there should, therefore, be some heat generated if Ampère's views were correct. Magnets are not noticeably hotter than their surroundings and Ampère, when faced with this fact, had to abandon his noumenal explanation.

It was Fresnel who provided Ampère with a way out. Fresnel wrote in a note to Ampère that since nothing was known about the physics of molecules, why not assume currents of electricity around each molecule. Then, if these molecules could be aligned, the resultant of the molecular currents would be precisely the concentric currents required. Ampère immediately adopted his friend's suggestion, and the electrodynamic molecule was born. It is, however, a peculiar molecule. In some mysterious fashion, a molecule of iron decomposed the luminiferous ether that pervaded both space and matter into the two electrical fluids, its constituent elements. This decomposition took place *within* the molecule; the two electrical fluids poured out the top, flowed around the molecule, and reentered at the bottom. The net effect was that of a single fluid circling the molecule. These molecules, when aligned by the action of another magnet, formed a permanent magnet. Ampère did not say why molecules should act this way; for him it was enough that his electrodynamic model provided a noumenal foundation for electrodynamic phenomena.

There was no doubt that Ampère took his electrodynamic molecule seriously and expected others to do so too. In an answer to a letter from the Dutch physicist Van Beck, published in the *Journal de physique* in 1821, Ampère argued eloquently for his model, insisting that it could be used to explain not only magnetism but also chemical combination and elective affinity. In short, it was to be considered the foundation of a new theory of matter. This was one of the reasons why Ampère's theory of electrodynamics was not immediately and universally accepted. To accept it meant to accept as well a theory of the ultimate structure of matter itself.

Having established a noumenal foundation for electrodynamic phenomena, Ampère's next steps were to discover the relationships between the phenomena and to devise a theory from which these relationships could be mathematically deduced. This double task was undertaken in the years 1821–1825, and his success was reported in his greatest work, the *Mémoire sur la théorie mathématique des phénomènes électrodynamique, uniquement déduite de l'expérience* (1827). In this work, the *Principia* of electrodynamics, Ampère first described the laws of action of electric currents, which he had discovered from four extremely ingenious experiments. The measurement of electrodynamic forces was very difficult, although it could be done, as J.-B. Biot and Félix Savart had shown in their formulation of the Biot-Savart law. Ampère realized, however, that much greater accuracy could be achieved if the experiments could be null experiments, in which the forces involved were in equilibrium.

The first experiment, to quote Ampère, "demonstrated the equality of the absolute value of the attraction and repulsion which is produced when a current flows first in one direction, then in the opposite direction in a fixed conductor which is left unchanged as to its orientation and at the same distance from the body on which it acts." The second "consists in the equality of the actions exerted on a mobile rectilinear conductor by two fixed conductors situated at equal distances from the first of which one is rectilinear and the other bent or contorted in any way whatsoever. . . ." The third case demonstrated "that a closed circuit of any form whatsoever cannot move any portion of a conducting wire forming an arc of a circle whose center lies on a fixed axis about which it may turn freely and which is perpendicular to the plane of the circle of which the arc is a part." Ampère rather casually mentioned at the end of the *Mémoire* that he had not actually performed the fourth experiment, which was intended to determine certain constants necessary for the solution of his mathematical equation. These constants, it would appear, had been found by measuring the action of a magnet and a current-carrying wire upon one another and were sufficiently accurate to permit Ampère to continue his researches.

From these cases of equilibrium, Ampère was able to deduce certain necessary consequences that permitted him to apply mathematics to the phenomena. It was time to turn to the noumena once again and to complete the edifice by deducing from the noumenal elements those mathematical relationships that had been indicated by experiment. The flow of an electrical current, it will be remembered, was a complicated process in Ampère's theory. Positive electricity was flowing in one direction in the wire while negative electricity flowed in the opposite direction. The luminiferous ether was a compound of these two fluids, so that it was constantly being formed from their union, only to be decomposed as each fluid went its way. Thus, at any moment in the wire there were elements of positive electricity, negative electricity, and the ether. Ampère's current element (*ids*), therefore, was not a mathematical fiction assumed out of mathematical necessity, but a real physical entity. What his experiments had done was to tell him the basic properties of this element. The force associated with the element is a central force, acting at a distance at right angles to the element's direction of flow. From this fact it was easy to deduce that the mutual action of two lengths of current-carrying wire is proportional to their length and to the intensities of the currents. Ampère was now prepared to give precise mathematical form to this action. As early as 1820, he had deduced a law of force between two current elements, *ids* and *i'ds'*. He gave the formula

$$F = \frac{i \cdot i' \cdot ds \cdot ds'}{r^2} [\sin \theta \cdot \sin \theta' \cdot \cos \omega + k \cos \theta \cdot \cos \theta']$$

for the force between two current elements, making angles θ and θ' with the line joining them and the two planes containing this line and the two elements respectively making an angle ω with each other. At that time he had been unable to evaluate the constant k. By 1827 he was able to show that $k = -1/2$. The formula above could now be written

$$F = \frac{i \cdot i' \cdot ds \cdot ds'}{r^2} [\sin \theta \cdot \sin \theta' \cdot \cos \omega - 1/2 \cos \theta \cdot \cos \theta'].$$

When integrated around a complete circuit (as in practice it must be), this formula is identical with that of Biot and Savart.

It was now possible for Ampère to attack the theory of magnetism quantitatively. He could show that his law of action of current elements led to the conclusion that the forces of a magnet composed of electrodynamic molecules should be directed toward the poles. He was also able to deduce Coulomb's law of magnetic action. In short, he was able to unify the fields of electricity and magnetism on a basic noumenal level. The theory was complete.

Not everyone accepted Ampère's theory. His primary opponent was Michael Faraday, who could not follow the mathematics and felt that the whole structure was based on *ad hoc* assumptions for which there was no evidence whatsoever. The phenomenal part was accepted; even in France the electrodynamic molecule was regarded with considerable suspicion. The idea, however, did not die with Ampère. It was accepted later in the century by Wilhelm Weber and became the basis of his theory of electromagnetism.

After 1827 Ampère's scientific activity declined sharply. These were the years of anxiety and fear for his daughter's well-being, as well as years of declining health. He produced an occasional paper but, by and large, after the great 1827 memoir Ampère's days as a creative scientist were ended. He turned instead to the completion of his essay on the philosophy of science and his classification of the sciences. He must have derived some satisfaction from the fact that he had, almost single-handedly, created a new science to be placed in his taxonomic scheme.

NOTES

1. *Annales de chimie*, **90** (1814), 43 ff.
2. See *Bibliothèque universelle des sciences, belles-lettres, et arts*, **17** (1821), 83.
3. *Mémoires sur l'électrodynamique*, I (Paris, 1885), 48.

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II. SECONDARY LITERATURE. There is no adequate biography of Ampère. C. A. Valson, *André-Marie Ampère* (Lyons, 1885), and Louis de Launay, *Le grand Ampère* (Paris, 1925), are the standard biographies, but neither discusses Ampère's work in any detail. The eulogy by François Arago provides a survey of Ampère's scientific achievement from the perspective of a century ago. See his *Oeuvres*, 17 vols. (Paris, 1854–1862), II, 1 ff. For some modern appreci-

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AMSLER (later **AMSLER-LAFFON**), **JAKOB** (*b.* Stalden bei Brugg, Switzerland, 16 November 1823; *d.* Schaffhausen, Switzerland, 3 January 1912), *mathematics, precision instruments.*

The son of a farmer, Amsler was educated at local schools before going on to study theology at the universities of Jena and Königsberg. At Königsberg he came under the influence of Franz Neumann, whose lectures and laboratory sessions he attended for seven semesters. After earning his doctorate in 1848, Amsler spent a year with Plantamour at the Geneva observatory; he went from there to Zurich, where he completed his *Habilitation* and began his teaching career. For four semesters he lectured on various topics in mathematics and mathematical physics, then in 1851 accepted a post at the Gymnasium in Schaffhausen. From this he hoped to gain some financial independence as well as an opportunity for more research. In 1854 Amsler married Elise Laffon, the daughter of a Schaffhausen druggist who was well known in Swiss scientific circles. Henceforth he used the double form Amsler-Laffon. The change applied to Jakob alone and was not adopted by his children.

Until 1854 Amsler's interests lay in the area of mathematical physics; he published articles on magnetic distribution, the theory of heat conduction, and the theory of attraction. One result of his work was a generalization of Ivory's theorem on the attraction of ellipsoids and of Poisson's extension of that theorem. In 1854 Amsler turned his attention to precision mathematical instruments, and his research resulted in his major contribution to mathematics: the polar planimeter, a device for measuring areas enclosed by plane curves. Previous such instruments, most notably that of Oppikofer (1827), had been based on the Cartesian coordinate system and had combined bulkiness with high cost. Amsler eliminated these drawbacks by basing his planimeter on a polar coordinate system referred to a null circle as curvilinear axis. The instrument, described in "Ueber das Polarplanimeter" (1856), adapted easily to the determination of static and inertial moments and of the coefficients of Fourier series; it proved especially useful to shipbuilders and railroad engineers.

To capitalize on his inspiration, Amsler established his own precision tools workshop in 1854. From 1857 on, he devoted full time to the venture. At his death, the shop had produced 50,000 polar planimeters and 700 momentum planimeters. The polar planimeter marked the height of Amsler's career. His later research, mostly in the area of precision and engineering instruments, produced no comparable achievement, although it did bring Amsler recognition and prizes from world exhibitions at Vienna (1873) and Paris (1881, 1889), as well as a corresponding membership in the Paris Academy (1892). From 1848 until his death, Amsler was an active member of the Naturforschende Gesellschaft in Zurich.

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