The Idea of an Electromagnetic Field

1. Setting the Scene

In the early years of the 19th century Paris was the intellectual capital of the world and especially of the world of science. Amongst its great scientists there were such men as Laplace and Lagrange, Fresnel and Monge, Poisson and Ampère. The centre of Parisian scientific activity was the Academy of Sciences and at its centre was the energetic and warm-hearted François Arago. Politically it was a time of great turbulence and one might have expected that it was hardly a time for detached scientific thinking. The French Revolution had, as is the custom of revolutions, devoured its own originators, but surprisingly had left the scientists to get on with their own work. The high esteem in which science was held, even by the revolutionaries, had its roots in the ideas of the movement known as the 'Enlightenment', which was particularly strong in France during the second half of the 18th century. This movement sought release from the oppressive dogmatism of authority in Church and State and hoped to replace authority by a free society based on reason and the study of nature. Science was expected to become the new universal value system and as such was to be fostered and protected. In the midst of the wide-spread destruction of established institutions the revolutionaries showed their support for science by the foundation of the Ecole Polytechnique.

The scientists assisted their own survival by separating science from politics. Thus the brilliant mathematician and astronomer Laplace (1749-1827) was a royalist when he began his scientific career as a professor of mathematics at the age of 19. He then became an active supporter of the Revolution in middle age, a minister under Napoleon and in old age a supporter of the Bourbon restoration. However, neither the ideals of the Enlightenment nor the political skill of the French scientists can provide a sufficient reason for the supremacy of French science. That supremacy arose from the extraordinary coming together of a group of outstandingly creative scientists.

Another remarkable feature of the scientific world of the early 19th century was the close contact between scientists in different countries. In our age of instant electronic sharing of information it comes as a surprise that ideas spread nearly as quickly at that time as they do now, in spite of the relatively slow means of travel and postal communication. Perhaps the reason is that information and ideas are only distant cousins and ideas have an independent speed of propagation.

Visits of British scientists to France and other European countries were common. Michael Faraday's diary gives a graphic account of one such journey. He was 22 years old and had never been more than 12 miles out of London, when in October 1813 he set out with Sir Humphry Davy on a Grand Tour of Europe. He had been Davy's laboratory assistant for a year at the Royal Institution, where Davy was Professor of Chemistry. Davy had soon formed a high opinion of Faraday's abilities and since he expected to undertake scientific research during the tour he asked Faraday to travel with him. Davy was then at the height of his career as one of the foremost chemists of his time. He was 35 years old and had been knighted in the previous year. He was both a daring experimenter and a brilliant expositor. For his Bakerian lecture at the Royal Society he had been awarded a prize by the Emperor Napoleon in spite of the fact that England and France were at war! It is astonishing that Napoleon in the midst of all his other concerns should have taken an active interest in chemistry, more astonishing that he was informed of work in a foreign country and almost unbelievable that he made an award to an ‘enemy alien’.

Equally astonishing is the invitation to Davy to visit France and other countries under French domination. Davy’s party, which included his wife, were issued with passports allowing unrestricted travel and providing free access to scientific institutions and museums. In Paris Davy and Faraday were courteously received by Ampère and other eminent French chemists. These consulted Davy about a strange new substance similar to chlorine, a substance which Davy had previously identified as an element. He, with Faraday’s assistance, set to work on a sample of the new substance and after various tests including an attempt at decomposition using a voltaic pile, Davy declared the substance to be a new element to which he gave the name iodine. He at once sent an account of his analysis to the Royal Society in London. So it came to pass that a scientific paper written in France in cooperation with French scientists was sent to England during a war between the two countries! Clearly science was too important to be interrupted by war.

Faraday himself showed a remarkable detachment from the political upheavals going on around him. Davy’s Grand Tour took a leisurely 18 months and during that time Napoleon had been briefly exiled to the island of Elba and had then returned to France. Faraday has a casual entry about this in his diary. ‘I heard that Bonaparte was again at liberty. Being no politician I did not trouble myself much about it, though I suppose it will have a strong influence on the affairs of Europe.’ The crucial battle of Waterloo was fought a few weeks after Davy and Faraday had returned to England.

After three months in Paris Davy’s party travelled to the South of France, visiting historical sites and meeting people interested in scientific matters. From there they crossed the Alps in mid-winter, Davy and Faraday walking through deep snow. They experimented with electric eels in Genoa and undertook various chemical investigations in Florence. From there they moved to Rome and on to Naples. On the way back they visited Geneva, where they met the family of Gaspard de la Rive, who had a private scientific laboratory. Faraday formed a lifelong friendship with his son Auguste, although Auguste was only 13 years old at the time of the visit. The leisurely pace of the journey provided the opportunity for many such contacts, which combined human friendship with scientific linkages. Also it enabled Faraday to learn French and sufficient Italian to be able to read that language.

2. Oersted’s Discovery

Electrical and magnetic phenomena have fascinated thinkers from the beginning of history. With the rise of Western empirical science at the beginning of the 17th century these phenomena received renewed attention. The first scientific treatise to be published in England was William Gilbert’s book ‘De Magnete’ (1600), which propounded the view that the earth was itself a great magnet. Gilbert explained magnetism in terms of a region of ‘magnetic power’ surrounding magnets. This power was particularly concentrated near the ‘poles’ of the magnet. His views are a remarkable foreshadowing of Faraday’s views, but it is very unlikely that Faraday had read Gilbert’s Latin treatise. Gilbert also investigated electrical effects, which he attributed to a gaseous substance, whereas in his opinion magnetism was nonmaterial. He thought that there might be some connection between electricity and magnetism.

The study of electricity and magnetism was greatly advanced by the French physicist Charles Augustin Coulomb (1736-1806), who used his torsion balance to verify the inverse-square laws between particles of electric and magnetic matter. Coulomb explained electric interaction in terms of two electric fluids of opposite sign. Similarly magnetic interaction was, in his opinion, due to two magnetic fluids. The difference between electricity and magnetism was due to the fact that the electric fluids were free to move through matter, whereas the magnetic fluids were confined to the molecules of the magnets.

The motion of electric fluids had been studied by several investigators including Benjamin Franklin, but an entirely new chapter opened with the discovery of the electric pile by Alessandro Volta (1745-1827), who was Professor of Natural Philosophy at the University of Pavia. This provided scientists with a source of continuous electric current, whereas previously they had to rely on the transient discharge from electrostatic devices. Volta announced his discovery in a letter dated 20 March 1800 to the President of the Royal Society of London. Within two months of the receipt of Volta's letter Nicholson and Carlisle used a Voltaic pile to decompose water by electrolysis. In the same year Davy began a series of chemical investigations using Volta's discovery. For a while electricity became a branch of chemistry and Faraday's ideas of the nature of electricity were shaped by Davy's chemical researches.

However, in 1820 Hans Christian Oersted, Professor of Natural Philosophy at Copenhagen, used Volta's pile to make another startling discovery. He found that an electric current exerted a force on a magnetic needle in its vicinity. Oersted had been looking for a connection between electrical and magnetic effects. He made his discovery during a course of lectures entitled 'Electricity, Galvanism and Magnetism'. Oersted strongly believed in the unity of natural phenomena, but unlike the French scientists, who sought this unity in the mathematical precision of Newton's mechanics, Oersted was a follower of the German romantic movement known as 'Naturphilosophie', which dealt in amorphous notions rather than mathematics.

In Oersted's case this philosophy was actually an advantage, because the result of his experiment did not easily fit into Newtonian science. Oersted described his observations in terms of the 'conflict of electricity' taking place in the wire and its surrounding space. He stated that this conflict acts on magnetic particles and does so in circles around the wire. It all sounded very strange to followers of Newton and seemed to revert to the discredited ideas of Kepler, who had thought that the sun exerted a force which swept the planets around in their orbits. Newton had shown that planetary motion could be explained far more simply by the universal law of gravitation combined with the principle of inertia embodied in his laws of motion. The law of gravitation had become universally accepted as the norm of scientific method. Coulomb's inverse- square laws between particles of electric and magnetic matter fitted beautifully into the Newtonian scheme, whereas Oersted's did not. However, there was no doubt about his experimental results and the experiment could easily be repeated by other investigators.

3. Ampère's Current Elements

Oersted's results were published in July 1820 in a short monograph written in Latin. His results were described by Arago at the meeting of the Academy of Sciences in Paris on 11th September. Exactly a week later André-Marie Ampère gave a lecture in which he proposed the idea that Oersted's results could be explained by the fact that magnetism was due to the action of current loops in magnetic material. He proposed to show experimentally that helical coils of wire carrying current would behave like magnets. He followed this lecture by another one a week later, then by others on September25th, October 9th and 13th and November6th. In the second paper he showed that parallel currents attract each other if the current flows in the same direction and repel if the current flows in the opposite direction. This breathless series of investigations was consolidated in a famous paper published in 1825 and shows Ampère as a brilliant experimentalist as well as theoretician. He eliminated the effect of the earth's magnetic field by his astatic balance, invented the galvanometer for his measurements and used the null method of balanced forces to enhance the accuracy. The central result of his work was the development of a formula for the force between current elements acting along the line joining them and varying as the product of the currents and the inverse square of the distance between the elements. These current elements, regarded as particles, fitted beautifully into the Newtonian scheme. In the words of Maxwell, "the whole, theory and experiment, seems as if it had leaped, full grown and full armed, from the brain of the 'Newton of electricity'".

Ampère was 45 years old in 1820. He had an established reputation as a mathematician and as a chemist. Already at the age of 13 he had read the works of Euler and in order to do so he had had to teach himself Latin, which he followed by learning Greek. He had made valuable contributions to probability theory, the calculus of variations, partial differential equations and analytical mechanics. In chemistry he had arrived independently at Avogadro's hypothesis, had clarified the relation between atoms and molecules and done much experimental work, including a study of the properties of chlorine and iodine. He possessed a photographic memory and could remember complete sections of Diderot's encyclopaedia, which he had read as a boy. He had a deep knowledge of philosophy and Christian theology and in his later years he attempted to write an encyclopaedia in which he hoped to establish a general classification of all the sciences. There was no branch of knowledge that he had not in some measure made his own. In the words of Sainte-Beuve, 'he spoke as a blind seer of old would have spoken, if that seer had come after Newton.'

One of Ampère's characteristics was that he had immense powers of concentration followed by loss of interest in a particular subject. After 1825 he took little interest in electrical research.

4. Faraday's Rotations

News of Oersted's discovery reached England a few weeks later than France. Davy told Faraday about it on October 1st. Faraday worked more slowly than Ampère and allowed his ideas to be shaped by experiment, whereas Ampère used experiment to test his theoretical conclusions. During his experiments Faraday's attention was directed to the circular nature of the magnetic force around a conductor carrying current. He devised a simple experiment to examine the action between a bar magnet one end of which stood in a cup filled with mercury and a conductor that was free to move. To his great excitement he found that the conductor moved continuously around the magnet. Similarly, an inclined magnet could be made to rotate around a vertical conductor. Faraday published his results in October 1821. Ampère was tremendously impressed by Faraday’s experiments. In his preoccupation with forces between currents he had missed this result, but he now showed how to make a bar magnet rotate on its own axis. Ampère had no difficulty in applying his theory to Faraday’s results, but he differed strongly from Faraday’s explanation. A lively and friendly correspondence ensued between the two, but without agreement. The point at issue was whether the circular magnetic effect causing the rotation was a complex phenomenon that needed to be resolved into its constituent parts or whether it should be regarded as a simple entity. Ampère thought in terms of current elements, but Faraday did not believe that there were such objects. Many years later Oliver Heaviside (1850-1925), in his characteristically sarcastic manner called them ‘irrational current elements’, because no continuous current could flow in an open piece of wire. Heaviside proposed the idea of a ‘rational current element’ instead. His insulated elements were immersed in a conducting ocean. The current was constrained to flow through the element and then continued in the surrounding fluid and returned to the other end of the current element. The magnetic field of a Heaviside element could be calculated and shown to be the limiting value of the field of a Hertz dipole for zero frequency.

Whereas Ampère concentrated attention on the current in conductors and magnets, Faraday thought in terms of the ‘power’ exhibited by the action between the current and the magnet. It was not surprising that Ampère’s views were widely accepted and Faraday’s ideas were dismissed as mere speculation. Nevertheless Faraday’s rotational apparatus had shown that there was a complete linkage of the magnetic force with an electric current, which did not appear explicitly in Ampère’s formulation in terms of forces between current elements. The idea of linkage was central to future developments.

5. Electromagnetic Induction

For mathematicians Faraday’s ideas were unsatisfactory because they did not lead to calculations. That, however, did not unduly disturb Faraday who relied entirely on experimental observation. His rotational experiments had given him great confidence in the physical existence of the circular magnetic power around electric currents. That confidence was strengthened by further experiments with iron filings that made the ‘lines of force’ visible. During the next few years his other investigations took precedence over electrical ones with one exception, when Faraday heard of Arago’s discovery that a rotating copper disc produced a torque on a magnetic needle suspended above it. Various explanations were suggested, the most common being that the disc had become magnetic. Faraday thought that the effect might be due to electrical induction in the disc. He tried the effect of moving a current carrying conductor towards another conductor connected to a galvanometer, but could not detect any effect. That was in 1825. In 1831 Faraday’s friend Moll drew his attention to some interesting experiments with electromagnets consisting of coils wound on iron cores. The iron core intensified the magnetic force of the coil considerably. Also the polarity of the magnets could be reversed almost instantaneously by a reversal of the current. That suggested to Faraday that there was some kind of wave propagation. He decided to investigate the propagation of the magnetic state from one coil to another when both were mounted on the same iron core and discovered that there was an induced current in the second coil when a current was set up or stopped in the first coil. He was sure that this was a transient effect caused by a wave of electricity.

This crucial experiment in August 1831 was followed by a whole series of others, which showed that the induction of electric currents depended on the relative motion of conductors and of the lines of magnetic force linked with the conductors. With continuous rotary motion Faraday was able to produce a steady current in a rotating disc.

6. Action at a distance or action in a medium?

By postulating that magnetism was due to the action of electric current Ampère had greatly simplified Coulomb's notions of electric and magnetic fluids. His next simplification was to replace the interaction of currents and magnets by the interaction of currents. That removed the need for the unfamiliar circular magnetic action and gave instead forces in straight lines between linear currents. Given Ampère's mathematical skill it was a short step from this to the idea of current elements acting on each other like Newton's particles of matter. Newton's method of action at a distance between particles had been enormously successful in astronomical calculation and Ampère's contemporary Laplace was its great exponent. It was no wonder that the idea of action at a distance between current elements soon became the central idea of electromagnetism in France and throughout Europe. It is interesting to examine why Faraday's ideas ultimately displaced those of Ampère.

Newton's action at a distance involved his separation of geometry from matter. Space was for Newton a container of infinite size, which provided the background for physical phenomena, but did not by itself possess any physical features. Matter was something in space and independent of space. The distance between particles of matter was a straight line, because Euclidean geometry could be applied to space. In fact there was no other kind of geometry apart from Euclid's axioms.

The independence of geometry and physics was questioned by the great mathematician Carl Friedrich Gauss and his pupil Bernhard Riemann. They showed that Euclid's idea of parallel lines was not a unique axiom, because other consistent geometries were possible in which parallel lines could intersect. Riemann showed that in any particular geometry the local curvature could be measured in terms of a curvature tensor. Years later Einstein made use of this idea to explain gravitational force as the effect of space-time curvature. Geometry and physics had coalesced.

Ampère lived at a time when Newton's infinite Euclidean space was universally accepted, but the fact that his current elements were physically impossible showed that magnetism could not so easily be replaced by current electricity and that there was an intrinsic curvature in the geometry of electromagnetism.

Whereas Ampère was interested in concepts and mathematical elegance, Faraday relied on experiments and directed his attention to physical processes. His idea of lines of magnetic force is a 'field' theory and combines physical and geometrical notions. The lines of force are linked with the electric circuits. The geometry is flexible and accommodates curvature. Often such a field theory is thought of as involving a medium through which the field acts. But Faraday's field is not a medium in Newtonian space and separate from that space. Rather the lines of force define the space. Moreover they also define the time of the action as it propagates, whereas the time is hidden in Ampère’s current elements which treat current as a static effect and regard the interaction as instantaneous. Ampère did not realise that Faraday’s rotational experiment already displayed the effect of temporal duration. He thought of it merely in terms of static force, a thought that is in accordance with Newton’s separation of time and space. That may have prevented him from the discovery of electromagnetic induction.

7. Maxwell’s Dynamical Theory of the Electromagnetic Field

Maxwell expressed great admiration for Ampère’s work. Nevertheless he turned to Faraday’s ideas as giving a better understanding of the physical processes. He felt that these ideas could be expressed mathematically and that Faraday’s lines of force provided the key to the action and propagation of electromagnetic effects. He used Ampère’s term ‘electrodynamics’ but transferred it to the field rather than the conductors carrying current.

Maxwell replaced Faraday’s lines of force by tubes of flux which fill the entire space. This gave him a vector field and he distinguished between two kinds of vector. One of these was associated with the cross-sectional area of the tubes and gave the flux, while the other was associated with the length of the tubes and gave the intensity. In the modern terminology of differential forms Maxwell thus defined a two- form and a one-form. The product of these was a three-form associated with a volume, which gave the local energy density of the field. It is interesting that the differential forms rather than the point vectors correspond to the measurable parameters of the field and that they combine the vectors with the spatial features. Maxwell used the notation of quaternions, which is a type of vector algebra that includes a scalar component in the vector. However, his use of the vectors often suggests that he regards them as differential forms.

Maxwell noticed that there were two kinds of energy, magnetic energy and electric energy. The analogy with the kinetic and potential energies of dynamics led him to the use of the method of Lagrange by which he could operate with general coordinates and momenta without having to give a detailed description of the nature of electric charge and current. It also led to the idea of the displacement current associated with the electric flux, which links the electric charge to the field.

Maxwell frequently referred to the electromagnetic field as a medium. However, it is a serious mistake to regard his field as an attempt to fill Newtonian space with some sort of substance. He was sceptical about the various aether models that had been used to explain electromagnetism. His explicit statement is that when he uses mechanical analogies their purpose is illustrative and not explanatory. Only the references to energy in the field are to be understood literally, because all energy is the same. Both for Faraday and Maxwell the field is a description of the phenomena in space and time. Physics and geometry cannot be separated.

8. Time and the Electromagnetic Field

Maxwell’s equations reveal the close association of space and time in electromagnetism. In modern notation his vector field has three space components and one time component. The constant velocity of electromagnetic waves is a property of space and time and it was this property that led Einstein to his famous ‘thought experiment’ involving the impossibility of an observer travelling with the speed of light, from which he deduced that the speed of light must be the same for all observers.

Maxwell’s equations are invariant to the direction of time and do not distinguish between radiation and absorption. Time in Maxwell’s theory is measured in terms of frequency and therefore of wavelength. That makes it possible to treat time as analogous to a fourth space coordinate. The absence of the directionality of time is a feature of all the equations of physics except possibly the second law of thermodynamics. This is a serious defect in the explanatory power of these equations. In his book ‘From Being to Becoming. Time and Complexity in the Physical Sciences’ the Nobel Laureate Ilya Prigogine calls time the ‘forgotten dimension’ in physics. The direction of time is observable, but is not included in the science. Prigogine draws special attention to the need to include the direction of time in thermodynamic processes far from equilibrium, which are common in biology. He suggests that physics is incomplete. That incompleteness is a feature also of Maxwell’s theory in spite of its great achievements in clarifying the nature of space and time as well as leading to a multitude of technical devices and systems.

9. Conclusions

The Faraday-Maxwell field theory of electromagnetism has had a revolutionary effect on our understanding of the physical world. It has replaced Newton’s concepts of space as a featureless empty container and of time as the constant motion of a cosmic clock by a relational view of space-time as an aspect of observable processes. Space-time provides the connections that make physical phenomena observable. In some ways this field concept is counter-intuitive. We still tend to speak of objects *in* space and events *in* time, whereas we should perhaps speak of processes *with* space-time. Even 150 years after Maxwell many people still seek to explain the world by an analysis into its particles. The lesson of the ideas of Faraday and Maxwell is that there can be no isolated particles, because their behaviour and their meaning depend on their connectedness. The whole is bigger than the sum of the parts. That is an important conclusion which applies to life in general as well as to electromagnetism.

Percy Hammond
dingle@waitrose.com