

## James Clerk Maxwell

*The Scottish physicist James Clerk Maxwell (1831–1879) formulated important mathematical expressions describing electric and magnetic phenomena and postulated the identity of light as an electromagnetic action.*

James Clerk Maxwell was born in Edinburgh on June 13, 1831. His father, who was a lawyer, was first named John Clerk but adopted the surname of Maxwell upon his succession to an estate, Glenlair, situated near Dalbeattie. James was a quiet child "much given to reading, drawing pictures, chiefly of animals, and constructing geometric models." A favorite pastime was reflecting the sun about his room with a highly polished tinplate, an activity which seemed to presage his adult preoccupation with optical phenomena.

### Education and Early Researches

James's strange mode of dress helped earn him the nickname "Dafty" at Edinburgh Academy, where he was enrolled in 1841. His father, aware of his son's scholarly aptitude, began taking James to meetings of the Edinburgh Society of Arts and of the Royal Society. Through his school studies James had become interested in a problem in applied mathematics, the construction of a perfect oval. At the age of 15 he communicated a paper to the Edinburgh Royal Society, "On the Description of Oval Curves and Those Having a Plurality of Foci." He remained at Edinburgh Academy until 1847.

Optical studies occupied much of Maxwell's time in 1847. At Glenlair he experimented with Newton's rings, a chromatic effect produced by pressing lenses together, and studied the color variations of soap bubbles. In the spring of that year his uncle took him to see a demonstration of a "polarizing prism" and he engaged in observing the effects of polarized light by means of specimens of Iceland spar. A paper read to the Edinburgh Royal Society in 1850, "On the Equilibrium of Elastic Solids," was the outcome of these studies. There Maxwell described strains set up in elastic substances such as gelatin and compared his experimental results which had been optically obtained with his newly derived theory of such equilibrium. This work was written in Maxwell's third, and last, year at the University of Edinburgh; he had enrolled in 1847.

In 1850 Maxwell went to Cambridge University as an undergraduate. He enrolled at Peterhouse but in December moved to Trinity College. In due course he became a scholar of the college and a member of the select Essay Club, familiarly known as the "apostles" since its membership was limited to 12. He took the bachelor's degree in 1854. Following graduation Maxwell was elected a fellow of Trinity College and joined its staff of lecturers, with responsibility for the subjects of hydrostatics and optics. He also carried out optical investigations with tops which were proportionally colored and

rapidly revolved to determine the true mixture of colors.

### **Aberdeen and King's College Professorships**

Maxwell left Cambridge in 1856 to accept an appointment as professor of natural philosophy in Marischal College, Aberdeen. There he met Katherine Mary Dewar, daughter of the principal of the college. They were married in 1858. During the years of his Aberdeen professorship Maxwell continued his study of the theory of colors. However, a problem regarding the stability of the rings of Saturn also occupied much of his attention.

The French mathematician Pierre Simon de Laplace had shown that if Saturn's ring were a solid it could not be stable. Maxwell decided to study a hypothetical mathematical model of the planet in which the ring was "loaded" at one or more points. In this manner he found a solution which accounted for the motion of the ring on Newtonian laws of physics but which predicted that the loads would be visible as satellites. Eventually, however, he discovered an alternative solution which entailed a fluid ring or one constructed of a colloidal arrangement of separate small solid particles. For this work Maxwell received the Adam Prize offered by St. John's College in 1857, in honor of the discovery of Neptune by John Couch Adams.

The following year Maxwell's professorship was dissolved when Marischal College was amalgamated with King's College to form the University of Aberdeen. He obtained, however, the professorship of natural philosophy and astronomy in King's College, London. There his formal responsibilities to the college were quite demanding, involving regular evening classes for working men and artisans in addition to 9 months of lecturing for the regular students. Nevertheless he continued his scientific researches.

At the British Association meeting in Oxford in 1860, Maxwell exhibited a device for mixing colors of the spectrum. He also presented an important paper on Daniel Bernoulli's theory of gases. The theory depicted gas as consisting of a number of independent particles moving without mutual interference except upon collision. Maxwell demonstrated mathematically that the apparent viscosity of gases, their low heat conductivity, and the known laws of gas diffusion could be satisfactorily explained by this theory.

Maxwell resigned his professorship at King's College in 1865 and retired to Glenlair, where he produced some of his most important scientific writing. He presented his dynamic theory of gases to the Royal Society of London in 1866. His treatise on heat appeared in 1870, and the great work on electricity and magnetism was published in 1873.

### **Organization of the Cavendish Laboratory**

In 1870 the Duke of Devonshire, who was chancellor of Cambridge, indicated his desire to build and outfit a physical laboratory for the university. In accepting the offer, university officials established a chair of experimental physics for the laboratory directorship. Maxwell became the first director of the Cavendish Laboratory in 1871.

Two important investigations undertaken at the Cavendish Laboratory when it opened in 1874, and supervised personally by Maxwell, concerned the accurate measurement of electrical resistance. The first was the testing of Ohm's law, a mathematical statement of the linear proportionality between electrical potential and the product of electrical resistance and current. Prior to the Cavendish re-

searches there was no evidence that the law was more than a good approximation of the behavior of nature, nor was there any theoretical reason why the law should hold accurately over extended ranges of current or potential. The Cavendish investigations demonstrated the adequacy of Ohm's statement to within 1 part in 200,000 over large variations of these variables. Paralleling this work was an investigation of electrical standards and the determination of the ohm in absolute units of measure.

### **Influence on American Physics**

In the early 1870s Maxwell not only played an important role in the scientific renaissance at Cambridge, but he was also instrumental in encouraging the development of high-level experimental physics in America. Original researchers who could understand the sophisticated mathematical formalism of European physicists such as Maxwell were rare at that time in the United States. The most eminent American scientific publication, *American Journal of Science*, was largely devoted to geological, botanical, and zoological topics; its editors simply did not understand exact science and its methods.

This was the situation faced by Henry Augustus Rowland, a young civil engineer from Rensselaer Institute, when he attempted to publish some magnetic researches. The American Journal editors repeatedly rejected Rowland's papers, forcing him in desperation to write directly to Maxwell. Maxwell received Rowland's work "with great interest" and saw to its immediate publication in the *English Philosophical Magazine*.

When Daniel Coit Gilman set out to find a faculty for a newly endowed university in Baltimore in 1875, he heard of Maxwell's interest in Rowland's work. For Gilman this endorsement was worth more than a "whole stack of recommendations." Thus Rowland became the first chairman of the physics department at Johns Hopkins University and until his death in 1901 led the way in establishing high-quality experimental physics in America.

### **Other Researches**

Maxwell's work in optics, kinetic theory of gases, and electromagnetism forms some of his most important contributions to science. His paper "On the Theory of Compound Colours" of 1860 summarized numerous experiments with the colored tops mentioned above. By means of another device of his own invention, the "Colour-box," he investigated the effect of mixing given proportions of light taken from the spectrum. He showed that any given color sensation may be produced by combinations in due proportion of rays taken from three parts of the spectrum; that is, from three so-called primary colors. These experiments also tended to confirm the hypothesis that color blindness was due to the viewer's insensitivity to one of the three primary colors. For this work Maxwell received the Rumford Medal of the Royal Society of London.

The concept of discrete particles in his solution of the Saturn's rings problem may have led Maxwell to the study of gases; his first papers on this subject appeared in 1860. He pointed out that the velocities of different molecules of a gas, even if equal to start with, would become different in consequence of collisions with their neighbors. He therefore employed a statistical method of treating the problem in which the total number of molecules was divided into a series of groups. The velocities of all of the molecules constituting a group were the same within narrow limits. By taking the average velocity of each group into account, he was able to determine an important relationship be-

tween this velocity and the number of molecules in the group. He published papers on gas theory almost continuously until his death.

However, Maxwell is best remembered for his work on electricity and magnetism, which began with the important study of 1856 on lines of force as conceived by the English physicist Michael Faraday. Maxwell took Faraday's view that electrical and magnetic effects did not arise from attractions at a distance of electric or magnetic matter. Rather these effects were the means by which changes of some unknown description in an "ether" which filled all space became known to the experimenter.

Maxwell studied attractions of magnetic lines of force by means of a model based on the vortices or whirlpools of a fluid or mobile medium. This model was used as a mechanical illustration "to assist the imagination, but not to account for the phenomena." The centrifugal force of the vortices was accompanied by a tension directed parallel to the lines of force issuing from a magnetic pole. He found great difficulty, however, in conceiving of vortices revolving side by side in the same direction about parallel axes. The difficulty lay in understanding how contiguous portions of consecutive vortices could move in opposite directions.

Maxwell's well-known solution was to imagine that a layer of "particles, acting as idle wheels" was interposed between each vortex and its neighbor. Contiguous sides of the vortices then acted on the idle wheels to produce a direction of rotation opposite to that of the vortices themselves. The remarkable feature of this model discovered by Maxwell was that the action of the "idle wheels" could be used to analyze electric currents. His discovery yielded a mathematical relationship between electricity and magnetism.

Maxwell also studied dynamical changes in the lines of force and introduced the concept of energy storage and distribution in the ether. These ideas were developed in a great paper, "On a Dynamical Theory of the Electromagnetic Field," read to the Royal Society of London in 1864. He portrayed electromagnetic action as traveling through space at a definite rate in waves which were transverse to the direction of propagation. The paper was expanded into his classic *Treatise on Electricity and Magnetism* (1873), in which he postulated the identity of light as an electromagnetic phenomenon. The test of this theory in various experimental forms occupied the time of a large number of physicists throughout the world for the remainder of the century.

During the last years of his life Maxwell devoted much time to editing the *Electrical Researches of Henry Cavendish* (1879). He also wrote a textbook on heat and a small treatise on dynamics called "Matter and Motion." Among his other papers are some on geometric optics and several, published mostly in the *Transactions of the Royal Edinburgh Society*, on reciprocal figures and diagrams of force.

Maxwell died at Cambridge on Nov. 5, 1879. A memorial edition of his scientific papers was organized and published by the Cambridge University Press in 1890. Several lines from one of his essays written at Cambridge in 1856 serve as a fitting memorial to this great electrical theorist: "They know the laws by heart, and do the calculations by fingers..... When will they begin to think? Then comes active life: What do they do that by? Precedent, wheel tracks, and finger-posts."