James Clerk Maxwell (1831–1879); Member APS 1875

FREDERICK SEITZ
President Emeritus, The Rockefeller University

> We shall find that it is the peculiar function of physical science to lead us . . . to the confines of the incomprehensible.
>
> *—J. C. M., 1860*[1]

> What is done by what I call myself is, I feel, done by something greater than myself in me.
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> *—Comment made by Maxwell to the Reverend Professor F.J.E. Hort in 1879 when terminally ill. See reference in n. 2; 421.*

AS MAXWELL'S FULL NAME might suggest, he was related to two families long prominent in Scotland.[2] The two sides, which had many cross-links, were well populated with individuals who had played important roles in the history of their country. The Maxwell name is believed ultimately to be of Anglo-Norman origin. Components of the two families had been staunch supporters of Mary Queen of Scots and had to flee to the Continent when her career came to an end. Later, a descendant of the Clerk family who had accumulated considerable fortune in France returned and acquired several large estates, particularly in the Midlothian area in southeastern Scotland, south of the Firth of Forth. The community of Penicuik there was regarded as the family seat. The associated Clerk estate comprised about seven thousand acres. Some members of later generations were less effective in business matters, and much of the land had to be sold off to cover debts incurred in failed ventures. As a result, one of the members of the Clerk family established by law the principle that no member of the family could have possession of more than one of the estates at a given time. In this way, James Maxwell's father (Fig. 2), a younger brother whose original name was John Clerk, found himself the inheritor of the remnants of what had once been the magnificent estate of Middlebie and a major holding of the Maxwell family. This residue was located in Kirkcudbrightshire about sixteen miles southwest of Dumfries.

By a requirement of the grant that his newly acquired land main-

FIGURE 1. Maxwell in 1855 when a fellow of Trinity College. There are more extended versions of this photograph, in which he is shown holding a color top. (Courtesy of The Science and Technology Museum and the Science and Society Picture Library, Kensington, London.)

tain the tradition that it had belonged to the Maxwells, he took on the surname of Maxwell, as did later generations that held the land. For this reason we have Maxwell's equations rather than Clerk's equations of electromagnetism. John did not find the obligation onerous since he cherished the memory of a favorite grandmother, a Maxwell who had married into the Clerk family and who had once lived at Middlebie.

The Clerks, incidentally, formed a close friendship with James Hutton, the Scottish physician who revolutionized the approach to geology. Their help to him in his work was far from routine, for it

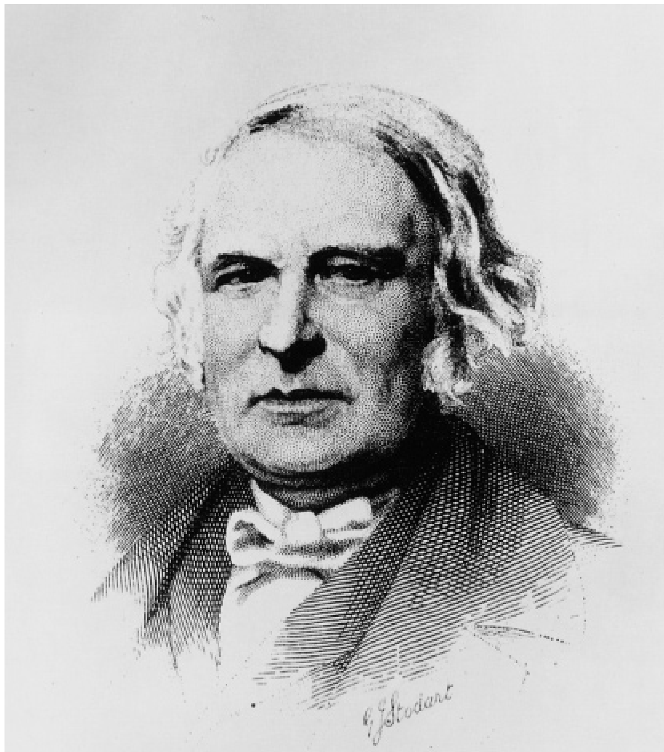

FIGURE 2. An etching of John Clerk Maxwell, James's father, at the age of sixty-six, three years prior to his death. It was made by G. I. Stodart and based on a portrait by John Watson Gordon. (Taken from the book by Lewis Campbell and William Garnett; n. 2.)

involved cooperation that included scientific observations at a fundamental level.

John Maxwell had studied law at the University of Edinburgh and spent his business time at Parliament House working on whatever matters came his way. He lived with his mother until her death in 1824 and then married Frances Cay, whom he met in Edinburgh through her scientifically oriented brother. The Cays were of English origin and had settled originally in North Charlton, Northumberland, just south of the border of Scotland, before a branch of the family moved to Edinburgh. She was a practical woman whose temperament matched his reasonably well. Her family had been Episcopalian, but she had no difficulty fitting into Scottish traditions as a member of the Scottish Episcopalian Church. John was a Presbyterian.

Actually John Maxwell was somewhat eccentric on some matters. For example, he designed his own clothing and shoes to be "practical" rather than conventionally ornamental, a policy he referred to as *Judiciosity*, implying great attention to details, not least technical ones. He was, however, thoughtful and charitable where the well being of others was concerned, and was highly regarded as a source of sound advice in the communities where he lived.

The Maxwells had two children, but only James, who was born in Edinburgh on 13 June 1831, survived infancy so he grew up as an only child.

Glenlair

Soon after their marriage, the Maxwells agreed, possibly through her initiative, that they would enjoy country life, and decided to rejuvenate what had been Middlebie as a working estate, within the limits of their means and energy. They added to the initial land area by purchase and constructed a small but livable stone house (Fig. 3) that was well designed for expansion.[3] The resulting estate comprised about two thousand acres. John Maxwell played a major role in every stage of the process (Fig. 4) and Frances supported him to the limit in her own way. One of the farms acquired carried the name of *Glenlair*, which they decided to adopt for the entire complex since the community of Middlebie, from which the original name of the estate had been derived, was far off in another shire as a result of the large contraction through sale of land.

Childhood

It follows that James entered childhood as a country boy living on an estate with an active farm. Precocity may have been common within

Figure 3. The appearance of the stone mansion at Glenlair as it stood after Clerk Maxwell had it enlarged, starting in 1867, on the basis of designs that had been made by his father. The modest original stone house, much upgraded, lies in the middle portion. Wings were added on the left and right. Unfortunately, the mansion and its contents suffered severe fire damage after Maxwell's death. Valuable correspondence and artifacts were lost. (Courtesy of C.W.F. Everitt; n. 3.)

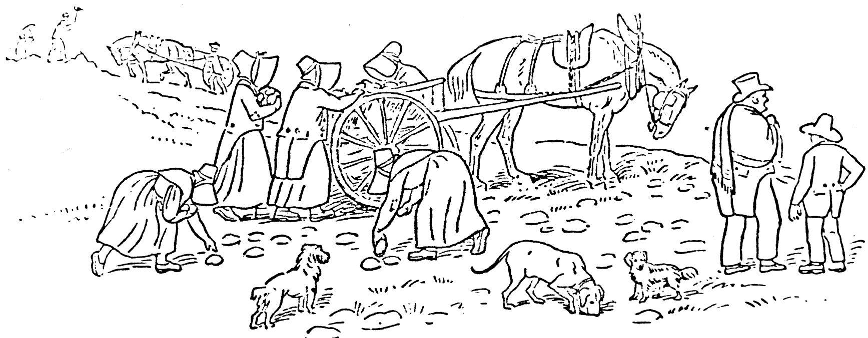

FIGURE 4. Clearing the farmland in Glenlair of boulders. Employment at this level was apparently free of sexual discrimination. The tall rotund man on the right is presumably the senior Maxwell. (Taken from the same source as Fig. 2.) Prior to the production of easy-to-use photographic cameras, many individuals possessing the talent enjoyed producing simple sketches of this type to record interesting events. This sketch was made by one of Maxwell's cousins, Jemima, who became a relatively celebrated artist. She possessed a satirical nature that Francis Everitt suggests is displayed in this cartoon.

the Maxwell-Clerk families, but his parents could not but note soon after he became a toddler that he had gifts far beyond the average. His good-natured curiosity about every living thing he observed was unbounded, and his examinations of flora and fauna were carried out

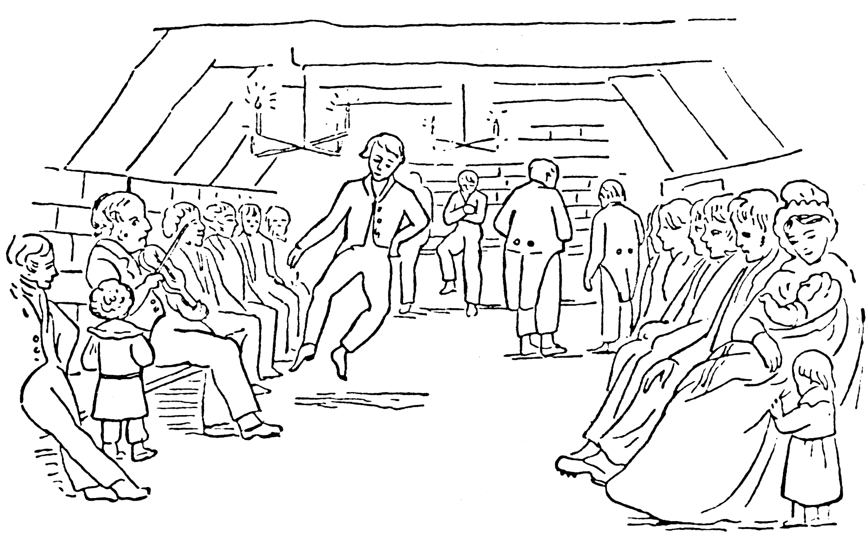

FIGURE 5. A country-dance party near Glenlair. Maxwell is the small boy on the left who is studying the violinist's technique intensely. (Same source as Fig. 2.)

FIGURE 6. Maxwell enlisting some of the household staff in basket weaving. (Same source as Fig. 2.)

in an intense but gentle manner. Mechanical equipment of any kind was fascinating (Fig. 5) and if new to him inevitably led to the insistent comment "Show me how it doos!" The servants and farm employees may have been driven to distraction (Fig. 6), but his father was always delighted to respond in whatever detail was needed.

Once he became literate, he enjoyed reading and creating poetry and fanciful short stories. His early written work was usually embellished with illustrations that, while immature, displayed good correlation between hand and eye. His poetry could be at the level of doggerel to commemorate an incident centered about the activities of a friend, or more high-minded and soul-searching.

Throughout his life his quest for knowledge and the understanding it conveyed was unbounded.

One of the family friends who came to Glenlair occasionally to hunt on the moors made the comment, with hunting in mind, that it was unfortunate that a boy who had this wonderful opportunity to enjoy country life to the full was so badly matched to it. He could not have been more mistaken. James loved every living animal, wild or domestic, on the estate, and found no place in his life at Glenlair for bloodsport involving his animal friends. Many individuals noted that he had an extraordinary ability to develop the friendship and trust of dogs (Fig. 7). They seemed to carry out his often complex commands with particularly intense enthusiasm and patience.

In addition to wondering how things worked, James enjoyed the pleasure of combining the activities of his mind with those of his own

FIGURE 7. Young Maxwell and his father training a dog. James was able to develop close friendships with dogs. This ability proved to be of value in his studies of vision. (Same source as Fig. 2.)

hands. For example, his mother was a celebrated knitter—an art much admired at that time. He quickly learned the technique and as a child began to turn out knitted work that in design and function displayed the workings of an exceptionally imaginative mind.

Outdoors, he soon developed considerable athletic prowess. He became an excellent swimmer and diver and a skilled ice-skater. At an early age he mastered the art of navigating the local ponds from within a tub using a paddle (Fig. 8), a means of navigation that required the development of special balance.

Death of Mother

A major tragedy struck the family in December of 1839 when Mrs. Maxwell died of intestinal cancer at the age of forty-eight. James was just eight years old and his father fifty-two. Surgery without anesthesia had been attempted without success. The psychological trauma incurred by both husband and son must have been enormous since the partnership of the three in all affairs had been very close. When informed that his mother was in heaven, James expressed relief that she was free of the intense pain she had been enduring. As might be expected, the loss brought father and son even closer together.

It is perhaps worth noting that James died of what appeared to be the same form of intestinal cancer at the same age as his mother. A genetic link seems likely.

FIGURE 8. Maxwell and a friend maneuvering through a pond in tubs, a sport he had developed. (Same source as Fig. 2.)

Having been raised within the framework of the sturdy religious traditions of Scotland, and under the influence of a religious mother, James devoted much of his life from childhood on to contemplating religious matters, and eventually emerged with strong convictions. He believed in the existence of a beneficent Creator to whom he regularly offered obeisance. It is not clear whether he was sufficiently egocentric to believe that his God focused immediate attention upon him. This was incidentally an intensely schismatic period in Scotland's religious history.

EDINBURGH ACADEMY

James's formal education had been in his mother's able hands. To continue it, a tutor was hired. The choice proved to be a complete disaster. The tutor had no understanding of the nature of his student, and concluded that he was basically stupid. When James attempted to restore the educational process to the methods used previously, the tutor resorted to use of the staff and other forms of physical violence. James held his calm, but the ever-observant aunts, particularly Jane Cay, quickly perceived the utter mismatch between student and tutor.

A decision, already partly formed, was made to have him attend Edinburgh Academy, a well-recommended preparatory school giving emphasis to mathematics and natural philosophy as well as Latin and

Greek, ethics, and the classics. James would live with an aunt during the school year and his father would commute as circumstances at Glenlair required. The school was not exactly what James needed at that stage of his development because there would be much emphasis on rote, but the death of his mother left little opportunity for other choices.

Bullies

James entered the academy a month after the term had started, by which time the groups of bullies in the various classes were well organized. As a newcomer meriting careful inspection and evaluation to see that he fitted in, he arrived wearing the somewhat outlandish country clothes of his father's special design, a clear but understandable error on the part of his otherwise sensitive aunts. Under scrutiny and questioning about his background and choice of clothing, he responded to the bullies as cheerfully as he might under the circumstances with vignettes of Scottish poetry, delivered in the vernacular and suitably adjusted for the occasion as he saw it. The peer group was baffled, decided he could never be a member of their elite class, and nicknamed him "Dafty," a designation that stuck throughout school years and was even remembered by some long after he had become world famous in his profession. He arrived home with his clothing in tatters. Another time, a group of bullies decided to rough him up for the sport. On this occasion he responded to their attack with such fury and physical energy that the group was glad to abandon its original mission.

In later years Maxwell displayed his lack of bitterness over such events by giving humorous accounts of the characteristics and activities of some of the bullies whose antics he had observed with interest.

In any event, James became somewhat of a loner at the academy, in addition to being bored with the rote. Fortunately his inner resources were enormous and his aunt's home offered him access to a magnificent library, including much literature that might not have been found at Glenlair. Moreover, once the rote learning in Latin and Greek had passed, he rapidly appreciated the richness and strength of the literature in the languages to which he was gaining access, and absorbed as much of it as other interests and activities permitted.

Lewis Campbell

Fortunately he did manage to make two lifelong friends of quite a different kind at the academy. One friendship, which was close, but began at the semi-professional level, was that with Peter Guthrie Tait, later also a distinguished mathematical physicist generally known as Guthrie Tait. On his own, Maxwell had learned earlier of the existence of the regular polyhedrons and promptly created cardboard models of the group. Tait undoubtedly saw them and, having similar interests, was drawn to this like-minded student in spite of his quasi-ostracism. They were to exchange professional material for discussion and criticism in a very friendly way throughout Maxwell's lifetime.

The other student, Lewis Campbell (1830–1908), who became Maxwell's most intimate friend and biographer,[2] was an individual of a

FIGURE 9. The Reverend Lewis Campbell in 1863. He was then a professor of Greek at St. Andrews University. His primary scholarly interests were in the classics, not in science. The close, lifelong, friendship with Maxwell dated from their years at the Edinburgh Academy in the 1840s. Their personalities were complementary. Although Campbell evidently viewed Maxwell with more than a degree of awe, he was sufficiently brilliant to be able to fathom many of the complex ingredients involved in the personality of his friend. Though Campbell's letters to Maxwell were lost, one gains some sense of their relationship from Campbell's statement about Maxwell in the Campbell–Garnett biography; see appendix A. (Courtesy of the St. Andrews University Library.)

completely different kind (Fig. 9). He was primarily interested in the classics, and eventually became a distinguished Greek scholar. He had observed Maxwell about the academy and obviously knew of the difficulties he had experienced on arrival, but was not a member of, or sympathetic to, the bullying peer groups. In other words he treated Maxwell as a more or less normal fellow student. An occasion arose in which Maxwell needed special help on some matter, perhaps related to some detail of academy policy or in connection with an action of the bullies. Campbell, who was conveniently nearby, volunteered his help, which was accepted. When he witnessed the warm look of gratitude that appeared on Maxwell's features as a result of an act of kindness, he was deeply moved, and appreciated the difficulties this sensitive individual had experienced as a result of the barbaric actions of some of his fellow students. Fortunately the two boys lived near one another and were soon walking together to and from the academy. Both were to be greatly enriched throughout their lives by the intimate friendship that developed.

According to Campbell's friends, who honored him in a number of obituaries, he was inclined to undervalue his own substantial abilities, which were much admired by others and won him many distinguished prizes for scholarship. In other words, he was somewhat introverted, and must have been fascinated with Maxwell's relatively outgoing and dynamic personality. As might be expected, Maxwell was in a sense the innovator of the pair, but Campbell was delighted to be a partner since life became broader and much more exciting. His open mind toward science is indicated by his close friendship with Thomas Huxley, a strong supporter of Darwin's theory.

On leaving the academy, Campbell spent time at Glasgow University, but completed his formal education at Oxford. While awaiting an academic post, he spent five years as vicar in the parish of Milford, Hampshire. Then and thereafter he was customarily addressed as "Reverend." The period as vicar terminated when he was appointed professor of Greek at St. Andrews, although he occasionally served as a clergyman. He enjoyed having small classes, and retired prematurely from the university in his early sixties when the university structure was reformed in ways that he found incompatible with his preferred style of teaching. He retired to northern Italy, but remained deeply engrossed in Greek scholarship, creating new translations of some of the great classics and generating biographical material about distinguished scholars.

What is important for our purposes is that he not only preserved all the voluminous letters he received from Maxwell over the years, but went as far as was possible to obtain copies of letters and related material Maxwell had sent to others. This collection formed the basis for his biography of Maxwell, which appeared in 1882.[2] It was written in cooperation with William Garnett, Maxwell's demonstrator during the latter's later years at the Cavendish Laboratory. Garnett so admired Maxwell that he burdened his son with the name James Clerk Maxwell Garnett.

Unfortunately, a fire at Glenlair in 1927, when it was occupied by rental tenants, appears to have destroyed any correspondence from Campbell that Maxwell had preserved. In any event it is to be noted that in Maxwell's letters to Campbell he always refers to him as "Dear Lewis" whereas his letters to Guthrie Tait are addressed as "Dear Tait."

In preparing the biography with Garnett, Campbell took what he viewed as a liberty to provide several pages in which he offers his own sensitive insights on Maxwell's personality, character, and talents. His statement, taken from the book, is reproduced in appendix A at the end of this memoir. Actually, it reveals much about Campbell's gifts as an analyst of others.

Maxwell's Emergence as a Scholar

The curriculum at the academy changed significantly in the fifth year. The language courses involved reading interesting material and, most important, included a course in geometry. Maxwell's period as an apparently indifferent scholar came to an abrupt end. He began to win prizes in English and Latin composition when he cared to compete. But above all he and Tait displayed a combination of knowledge and creativity in geometry that awed the instructor as well as other students. While Tait may possibly have exhibited some spirit of competition in their relationship, he could not help but admire Maxwell's remarkable talents and encourage the development of friendship.

First Published Research; Professor Forbes

It is well known that one can trace an ellipse with a pencil that is guided by a taut string anchored at two points—the foci of the ellipse. Maxwell became fascinated with this form of geometrical construction and began to extend it to the development of more complex ovals. He was apparently inspired by the attempts of a professional artist to derive ovals by an inferior method of approximation. Some of Maxwell's creations involved more than two anchor points. In other cases the string was taut and had two anchor points, but extra loops encircled the pencil so that the figure transcribed was not a simple ellipse. The mathematics accompanying each geometrical form was described in detail along with the mode of construction.

When his father saw a more or less fully developed version of the work, he decided to show it to Professor James D. Forbes, a physicist at the University of Edinburgh (apparently known locally as "The College"). Forbes not only was impressed, but discussed it with his mathematical colleagues. Research revealed that young Maxwell's paper represented an extension of a series of studies carried out by René Descartes in the seventeenth century. The senior mathematicians agreed that James Maxwell's paper should be presented in his name at a meeting of the Edinburgh Royal Society. Professor Forbes read the paper on Monday, 6 April 1846. James was then fifteen years old. In a sense his professional career had begun.

University of Edinburgh

Young Maxwell spent the years between 1847 and 1850 at the University of Edinburgh, where he enjoyed a much friendlier atmosphere and a much richer fare than he had at the academy. He was attracted there by the presence of Professor Forbes as well as the convenience of remaining domiciled in Edinburgh. In addition to the usual studies immediately related to science, languages, and history, which were treated in a solidly practical manner, he became deeply immersed in issues related to logic, ethics, religion, and metaphysics. On the side he continued to carry out experiments and to explore developing areas of science that struck his fancy.

In the meantime, Lewis Campbell went to the University of Glasgow, as mentioned earlier, but left for Oxford at the end of a year upon winning a highly prized scholarship there. Similarly, Tait went up to Cambridge after a year at the University of Edinburgh.

Cambridge University (1850–56)

Early on, Maxwell's father had thought that his son should prepare for law, wherever it might lead, but it had become obvious that the latter's interests were so wide that he should receive the broadest possible education. As a result he entered Cambridge University in the autumn of 1850. At first he selected Peterhouse, where many of the mathematically oriented students congregated, but he soon shifted to Trinity College, probably under the influence of Professor Forbes at Edinburgh, who greatly admired and was a close friend of the master, William Whewell. Trinity also offered better opportunities on several scores, including the presence of brilliant scholars in many fields outside, as well as in, the sciences. Maxwell rapidly made friends in many disciplines and, having a mind with the qualities of a sponge, expanded his horizons broadly. He particularly enjoyed association with those in the humanities, but was prepared both to learn and expound more than competently in many fields.

At the University of Edinburgh, he had developed a reputation as a brilliant generalist as well as mathematician, which had helped open doors at Cambridge. For example, within a year or so of entering Trinity he was invited to be a member of the Select Essay Club, a group of twelve self-appointed intellectuals, nicknamed "The Apostles," widely viewed as the most distinguished group of scholars in the college at a given time. The club continues to the present time, having passed through a spotty period in which it became the focus of activities of "fellow travelers" such as Philby.

The broadening of interests did not imply that Maxwell was deserting science. He in fact took all necessary steps to become prepared to compete in the well-known tripos examinations in mathematics, as well as for other prizes. Moreover, to please his father, he hoped to win a college fellowship. Still further, he brought to Cambridge a substantial part of the equipment he had used in his experimental research at home. Its presence within the college walls seemed out of place to many of the students, who had apparently forgotten that Isaac Newton was involved in experiments in both optics and alchemy while at Trinity College.

Incidentally, Maxwell witnessed the operation of the Foucault pendulum in Cambridge in 1851, soon after the initial demonstration in Paris. It undoubtedly provided him with an enormous thrill since it is precisely the type of demonstrational device he admired and sought to create when appropriately inspired. Unfortunately, his letter to his father describing the experience appears to have been lost in the fire at Glenlair, along with the correspondence he received from Campbell. Fortunately, his father's response has been saved.

Once it was clear to Professor Forbes, his guiding friend at the University of Edinburgh, that Maxwell would compete in the tripos examination, Forbes wrote to his friend William Whewell, the master of Trinity, urging him to help Maxwell gain polish in the course of preparation. Forbes emphasized that this remarkable young Scot tended to be "uncouth" in approaching most of his activities. Fortunately, whatever polishing Maxwell's capable mathematics tutor, William Hopkins, and his colleagues may have attempted left Maxwell's creative capacities undiminished. In later years, Hopkins commented that Maxwell "never made a mistake!"

Honors

It may be added that Maxwell placed second in the tripos, shared the principal mathematics prize, the Smith Prize, and won a fellowship, so that the honor of Scotland and his father's pride were preserved. This incidentally was the first time in its eighty-year history that the Smith Prize was shared. All this intense and diverse activity was not accomplished without a price, however, for he suffered what would probably be called a nervous collapse during the spring of 1853. Fortunately he received excellent care and had recovered reasonably well by autumn. One of his loving aunts recommended a daily glass of port wine.

Having won a fellowship in Trinity College, he decided to remain for a period while deciding what to do next. He took on modest teaching duties, stayed in close touch with university activities that interested him, and continued to struggle with a complex range of research activities, some of the most important of which will be related presently.

Marischal College (1858–60); Death of Father

Although he could have remained at Cambridge as a fellow, or don, somewhat longer, he decided that the role was too confining for him. As a result, he applied and was accepted for an open post as professor of natural philosophy at Marischal College in Aberdeen in 1856. Among other important matters, this brought him closer to his father, who was no longer in good health. Moreover, the post would give him much freedom for long visits to Glenlair.

Unfortunately, his father, in his late sixties, died quite suddenly during the transition period. This left young Maxwell, now twenty-four years of age, with an even deeper sense of loss, as well as the obligation to bring under control the many business affairs, including those related to Glenlair, that his father had attended to. Nevertheless, he picked up the reins at Marischal and was soon engaged in the tasks there.

Marriage; King's College London (1860–65)

In the process of recovering from the loss of his father, he was befriended by the family of the principal of the college, Mr. Dewar, and fell in love with one of the daughters, Katherine Mary Dewar. This led to what Lewis Campbell described as "a married life which can only be spoken of as one of unexampled devotion." They were married in June of 1858; the union endured (Fig. 10) until his premature death in 1879. His wife enjoyed participating in his research, although she suffered disabling nervous attacks from time to time.

In 1860, the government decided to cut back on the number of colleges that were being supported, and closed down Marischal, leaving Maxwell temporarily without a post. At the same time, Professor James D. Forbes, his longtime friend at the University of Edinburgh,

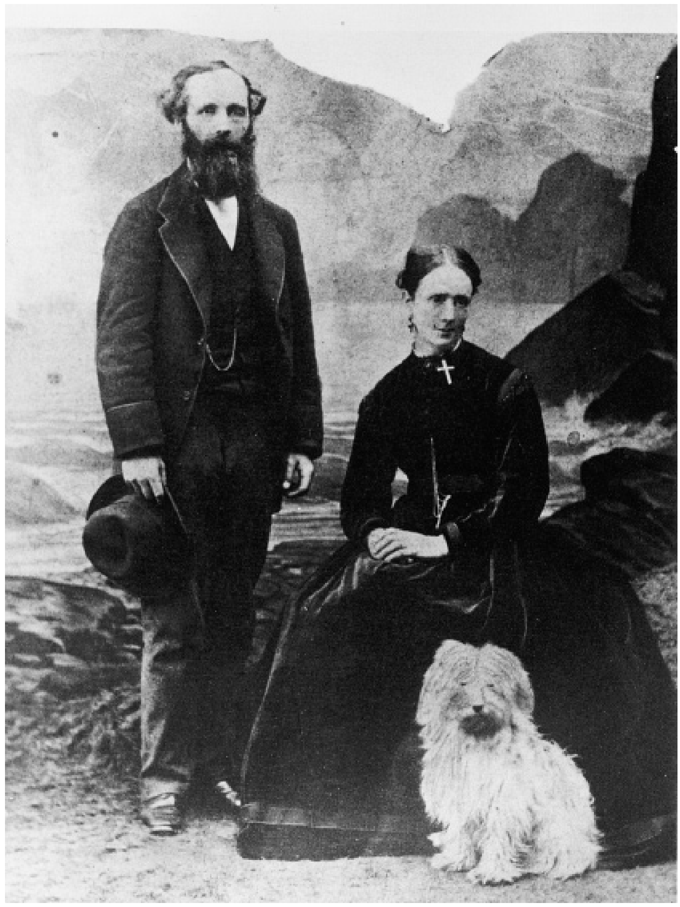

FIGURE 10. A photograph of the Maxwells taken in Scotland about 1875. (Courtesy of C.W.F. Everitt; n. 3.)

decided to take leave from the university during a bout of ill health, and accepted the post of principal of the University of St. Andrews, then regarded as a less onerous post. Maxwell applied for the open position, but it went instead to his old friend and former classmate at the academy, Guthrie Tait. Presumably the selection committee felt that Tait was the better all-around teacher for the level of student at the college. The decision had no noticeable effect on the lifelong friendship of the two. They continued to carry on a lively semiprofessional correspondence in the same genial way as before.

As an alternative, Maxwell accepted a professorship at King's College, London, a position he held for five years, until 1865, when he decided to alter his style of life completely, as will be related. He contracted smallpox just before taking up his position in London, and was given dedicated solitary care by his wife.[4]

The Start of a Research Career; Color Vision

Until the completion of his undergraduate years at Cambridge, most of Maxwell's various research programs in science were carried out primarily for pleasure and self-illumination, with one significant exception. When he entered the University of Edinburgh, Professor Forbes was much interested in the theory of color vision and was pleased to have Maxwell join in his research program in 1849. In fact, Maxwell had become much interested in light and the general field of optics somewhat earlier as a result of a visit to the laboratory of William Nicol, who, along with an international group of scientists, was making rapid advances in the development of optical equipment and associated research.

Newton had concluded that light was corpuscular in nature, and had developed a circular color chart made up of a number of different colored segments that could be combined to form other colors. In Newton's chart, the colors situated diametrically opposite one another could be mixed to form white or a shade of gray.

Thomas Young (1773–1829) later challenged Newton's form of corpuscular theory and succeeded in demonstrating that light possesses wave properties.[5] Young also proposed that normal human vision depends on the sensitivity of individual components of the retina to red, green, and blue hues. All other colors can be derived as a mixture of the three, and represented in a triangular diagram or chart in which the three sides are calibrated to indicate the fraction of each of the three primary colors present in any given color. His early research was also based on the use of colored paper in which the observed color is the result of subtraction of all colors except the combination in the observed range. Helmholtz showed, however, that one could carry out such studies more precisely with spectroscopically isolated portions of the solar spectrum.

In their original work, Forbes and Maxwell had used triads of sectors of colored paper mounted on a rapidly spinning disk in the search for color combinations that would produce white or gray when present in appropriate ratios. Unfortunately, Forbes became ill and the program on color vision initiated by him at Edinburgh was abandoned. It remained well fixed in Maxwell's mind, however, and he returned to it in 1854 as a fellow at Cambridge. He decided to follow the basic leads established by Young.

At first, he employed, as previously, a rotating wheel, or spinning

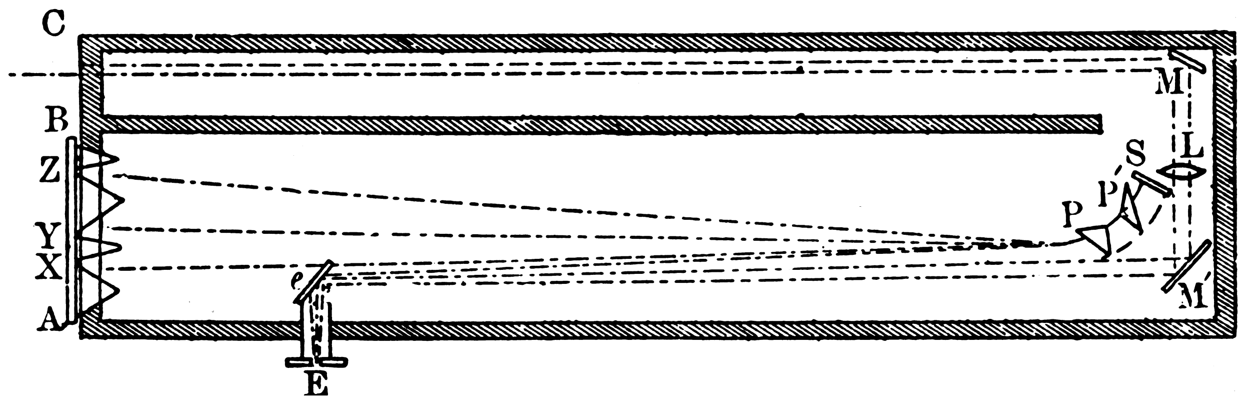

Figure 11. Schematic plan of Maxwell's color box viewed from the top. It contains two chambers separated by a baffle that extends as shown for most of the length of the box from left to right. Light that enters at window C will, with the aid of mirrors and lenses, be directed to the viewing eyepiece E. The outer end of the eyepiece at E contains an insert with a fine vertical slit. The area A-B is blocked to the passage of light except for the presence of three separated, adjustable, vertical slits X, Y, and Z. The slits are contained in brass mountings or shutters that permit them to be made wider or narrower or to be moved sideways to a degree (up and down in the diagram). Adjustments in slit-width are made with a scale graduated in units of 0.005 inches. When the full spectrum of the sun falls on the area A-B, white light enters each of the three slits in relative amounts determined by their widths. A carefully designed mirror and prism system P-P′-S, shown in the lower right-hand portion of the diagram, directs a single, different, range of wavelengths from each of the slits to the viewing aperture E. In a typical case the portion of the ray that passes through slit A and reaches E may lie in the red portion of the solar spectrum; that which originates in slit B may lie in the green portion; and that which originates in C may lie in the blue portion. In his studies of the composition of variously colored forms of light that were introduced into aperture C, Maxwell did in fact use mixtures from selected portions of the red, green, and blue parts of the solar spectrum as the basis for analysis. In a typical operation, the viewer admitted the light under investigation into aperture C and viewed it through the eyepiece E. The intensity observed at E could be varied by adjustments made at the entrance C. The slits X, Y, and Z, which respectively admitted red, green, and blue light, were then adjusted in width until the mixture of the three observed at E matched that of the color under analysis. Readings of the corresponding widths of the slits X, Y, and Z provided a permanent, quantitative record of the result of the experiment. See Figure 12 as an example of the results of this research. (Reproduced from the book by Campbell and Gannett; n. 2.)

top, with sectors of colored paper, but eventually developed in sequence a series of ever more sophisticated viewing boxes (Fig. 11) in which he could combine triads of narrowly isolated portions of the solar spectrum in arbitrary proportion in the investigation of color mixing. He had become a superb designer of scientific equipment.

The triads were selected from the blue, green, and red portions of the solar spectrum. This permitted Maxwell to develop a precise two-dimensional color chart of triangular form. Colors, including shades of white or gray, that could be derived from appropriate mixing of his three selected primaries, lay inside the triangle. Those to which one of the primary colors had to be added in order to match a mixture of the other two primaries were placed outside the triangle at a position determined by the combination of primaries.

Incidental to this research, he confirmed the source of red-green color blindness and demonstrated the existence of other types of this blindness. He also observed variations in color sensitivity among normal individuals (Fig. 12). In careful non-destructive observations of the

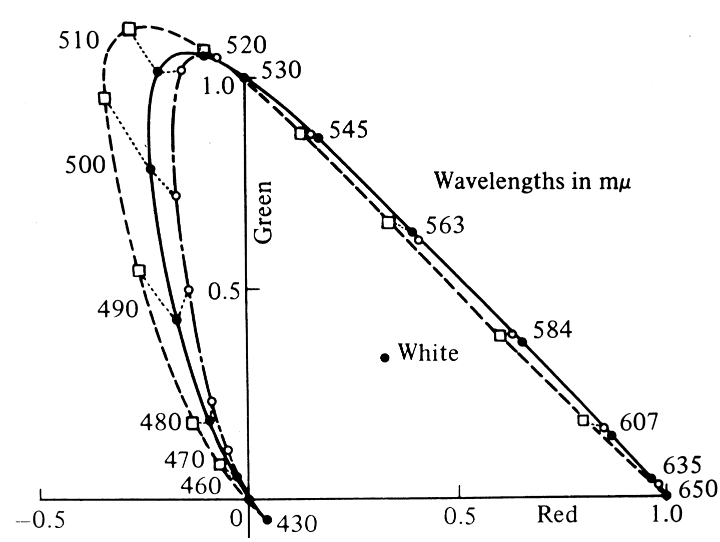

FIGURE 12. A diagram showing the mixtures of three colors selected in the blue, green, and red portions of the solar spectrum that match other colors in the solar spectrum as determined by Maxwell's wife, Katherine (open circles), König and Abbey (squares), and for a "standard" observer (black dots). The values of the wavelengths studied are given in millimicrons. Variations between observers are common within a randomly chosen group of individuals. Mrs. Maxwell's vision conforms closely to that of the standard. Maxwell measured her color vision with the use of his color-matching spectroscope. This diagram, created by C.W.F. Everitt, appears in his book. (Courtesy of C.W.F. Everitt; n. 3.)

structure of the retina he observed, apparently for the first time, the special region that contains the macula. The family dogs were usefully and patiently cooperative in this aspect of his research, allowing him to inspect the details of their retinas with focused light as though it were a special privilege to cooperate in the experiments. Maxwell received the Rumford Medal of the Royal Society of London in 1860 for this research.

To advance his own theoretical understanding, and partly for the edification of his friends, Maxwell designed and had constructed a very ornate top, which had a circular metal disk mounted at right angles to the axis of rotation and centered on that axis. A number of segments of brilliantly colored strips, selected in proportions that would produce white or off-white gray when the top was spun, were mounted on the disk. The surface of the disk appeared to be grayish as long as the top was spinning in its quiet "sleeping" stage. Once friction finally took hold and the top became less stable, the brilliantly colored strips would flash on and off to view, creating a dramatic display. Maxwell developed a detailed theory of the effects observed, relating them to nutation and precession of the top. The antics of the top became an object of much attraction in Trinity College and elsewhere. The theory underlying the behavior of the top was redeveloped later and patented by the Honeywell Company.

Saturn's Rings

The planet Saturn had served as a special source of mystery since the time of Galileo. Improvements in telescopes had finally achieved sufficient resolution to demonstrate the presence of rings, but the nature of their structure was still uncertain by the time of Maxwell. In the previous century, the great mathematician Pierre Laplace had determined some very special conditions under which the rings could be solid, but the truth remained unresolved.

Cambridge University had an award, the Adams Prize, that could be given to an individual who presented a suitable essay treating a topic determined by the award committee. In 1855, the committee offered it to the individual who could shed substantial light on the nature of the rings. Their choice seems to have been stimulated by observations indicating that the ring structure was not static, but changed with time.

Maxwell decided to respond to the challenge, and picked up the problem where Laplace had left it. In doing so he promptly displayed his great command of Newtonian mechanics. First, he demonstrated that it was highly unlikely that the rings were solid, since the gravitational gradient arising from the main body of the planet would generate stresses that normal matter could not withstand. The assumption that the rings were gaseous, liquid, or plastic in nature fared no better under realist conditions because of the development of destabilizing waves. He concluded that the rings consisted of what were effectively clouds of small solid satellites. His well-developed essay was awarded the prize in 1859. Francis Everitt has noted that the scientific paper submitted for the prize is the longest Maxwell ever wrote, suggesting that in the psychological sense he was attempting to compensate for sharing the Smith Prize rather than winning it alone.

Statistical Mechanics; Pathfinder

Material found among his notes demonstrates that Maxwell did give some thought to the statistical distribution of energies that might be expected to develop in the clouds of "brickbats" in the rings of Saturn as a result of collisions, but he did not pursue the matter at the time. The topic was rekindled in his mind in 1859, however, when, after completing the essay on Saturn's rings, he read a paper by Rudolf Clausius, who was struggling to develop an atomic theory of gases in which the pressure exerted by a gas against the confining walls of a vessel was assumed to be the result of reflective bombardment by individual atoms that are in a degree of dynamic motion related to the temperature. For simplicity, Clausius had assumed that the atoms had the same, average energy. In addition he had made some reasonable assumptions regarding the mean free path between atomic collisions in order to estimate diffusion rates of atoms in the bulk of the gas.

Maxwell had long supported the atomic theory of gases. He entered the research program at this point using simplified models of a perfect gas in which the principal interaction between molecules occurred during collisions. On the assumption that the three orthogonal components of the velocity distribution are independent, he demonstrated that the distribution of velocities, v, among the molecules in the assembly would be governed by a function of the form

$$f(v) = Av^2\exp(-v^2/B)$$

in which A is related to the density of atoms and B is related to the average kinetic energy of the atoms, or the temperature. This function, which is similar mathematically to those that occur in many simple statistical problems, such as the distribution of darts about the center of the dart board in the well-known game, is commonly designated the Maxwell distribution law, or, alternately, the Maxwell-Boltzmann law, in recognition of the work of Ludwig Boltzmann (1844–1906), who greatly extended research on statistical assemblies.

When Maxwell used his distribution law to calculate the viscosity of his perfect gas, that is, its resistance to shearing forces, he was surprised to find that the result was independent of pressure, or density. The same was found to be true of thermal conductivity. Careful measurements of the viscosity and thermal conductivity of several gases, carried out with the aid of his wife, confirmed the theoretical results for appropriate lower ranges of pressure. This success demonstrated that the theory could be used for other calculations. For example, he used it to determine the mean free path between atomic collisions and the rate of gaseous diffusion, thus opening the route to the systematic study of transport phenomena. It also provided a basis for estimating atomic size.

The introduction of statistical factors into the treatment of appropriate physical problems must be regarded as one of Maxwell's foremost contributions to the advance of physics. For example, it opened the doors to a deeper understanding of the laws of thermodynamics, particularly the importance of entropy. Maxwell was fully aware that he had crossed a major bridge into a new world, although he could not have been expected to envision more than a glimpse of what was to come in the decades ahead.

Maxwell's "Demon"

One of the ways in which Maxwell illustrated the important role statistical variability could play in a physical system is linked to the operation of what has come to be called "Maxwell's Demon," a term he did not invent but apparently came to accept. Consider a vessel containing two equal volumes, A and B, separated by a partition having a small trap door. Also assume that the two volumes contain identical amounts of the same gas at the same temperature and pressure so that they are in thermodynamic equilibrium with one another. Imagine a device (the "demon") that operates the trap door in such a way that fast, that is, energetic, atoms are preferentially allowed to pass from A to B, whereas slow atoms are preferentially allowed to pass from B to A in equal number. As an end result the average energy of the atoms in compartment B will rise whereas that of those in A will fall, so that the gases in the two compartments will no longer be at equilibrium. We know from more modern considerations centering about the link between entropy and measures of information that the mechanism operating the trapdoor would have to do so in ways that preserve the laws of thermodynamics, but a significant point had been made.

Above all, Maxwell had partly opened the way for the treatment of dynamic systems that are being driven out of thermodynamic equilibrium and seek to return to this equilibrium. Boltzmann was to make the next significant advance. Incidentally, Maxwell made jocular comments in private to his more intimate scientific friends regarding Boltzmann's early attempts to link mechanics and thermodynamics, but had gained great respect for Boltzmann's developing work by the 1870s.

The Field Equations of Electromagnetism

Maxwell's derivation of the classical field equations of electromagnetism represents his greatest triumph among many. The accomplishment places him in the rank of the very great, such as Galileo, Newton, and Einstein, in his profession. He was not without competition in the attempt to find a way to unify the field; many physicists were involved in the process. Maxwell selected his own route with a minimum of detailed external guidance, and produced the foundations for a profound revolution in the future development of physics.

It is to be emphasized that the investigators working on the problem were thoroughly ignorant of many of the most important issues that entered into it. There was still a great debate as to whether atoms actually exist as discrete entities. None of the fundamental particles had been isolated. It could only be assumed that electricity consisted of some type of fluid that came in two forms, positive and negative.

One did not know what kind of physical structure, if any, should be associated with a vacuum. Eventually, the notion that a vacuum should possess some form of mechanical structure became prevalent. The existence of the medium was covered by the term "aether," or "ether" in modern terms. Precision of detail was absent.[6] It seems clear that Maxwell was prepared to accept the concept of the ether as then understood and to speculate about its possible nature and capabilities. Moreover, in his later years he displayed much interest in experiments designed to detect any relative motion between the orbiting earth and the hypothetical ether. In any event, he was prepared to move in any direction that seemed reasonable to him in trying to consolidate the field of electricity and magnetism.

Incidental to his interest in conceivable physical properties of the ether, he was fond of constructing mechanical devices composed of rods and gears that in his mind mimicked some observed physical process, such as the interaction of electric and magnetic fields. This practice, which may seem quaint by present-day standards, was presumably developed through the belief that the properties of the ether as a medium of transmission of forces could possibly be explained in quasi-Newtonian terms.

There are two major components to the study of electricity, namely the static and the dynamic. The first is represented by the properties of the static electrostatic charge commonly experienced on dry days and by the type of static bipolar magnetism (north and south) found in the compass needle or the common horseshoe magnet. Independent studies of the properties of static electric charges and static magnetism, made before the dynamic effects were discovered, led to two different scales of measurement.

The second, or dynamic, aspect is illustrated by two observations: a straight wire carrying an electric current is surrounded by a circular magnetic field that is oriented at right angles to the wire and is centered symmetrically about it (Ampère's law); an electromotive force that can produce an electric current is generated in a circular wire that experiences a changing magnetic field of the appropriate kind within the circular area encompassed by the wire (magnetic induction).

Since static electric charges and individual magnetic poles interact in each case with inverse square laws of force, as is true for gravity at the normal laboratory level, there was a strong tendency among investigators to try to consolidate the laws of electromagnetism through a technique that had been used in handling gravitational problems and designated "the method of action at a distance." Maxwell avoided this route,[7] perhaps because he saw that it was leading nowhere in the hands of others.

Starting Search; Michael Faraday

In looking for alternatives, Maxwell began corresponding with the aging, brilliant physical chemist Michael Faraday (1791–1867) in 1857. Faraday, along with the American physicist Joseph Henry, had discovered magnetic induction and offered theories concerning the nature of magnetic fields. It must have seemed somewhat strange to the older man, who had emerged from the working class and had accomplished much with the use of relatively homespun but well-founded theories, to be approached so earnestly by this Cambridge fellow, forty years his junior, who was already achieving much distinction as a creative physicist. The encounter proved to be crucial, however, for it inspired Maxwell to search in an entirely new direction and thereby generate a major revolution in the course of physics.

Faraday, who possessed an amazing physical intuition, supported the view that space was permeated with a medium that could contain stresses and transmit waves. He proposed that what he termed lines of force were produced within that medium in a three-dimensional manner by electric charges and sources of magnetism. The various forms of electromagnetic phenomena were to be understood in terms of pressure exerted by these lines upon one another through the medium. In this connection Faraday was very skeptical about Newton's treatment of gravitation, which assumed instantaneous action at a distance. He believed that gravitation would eventually be understood more completely in terms of force fields with finite rates of propagation. (See the discussion of these matters in Faraday's own words in appendix B, taken from the book by Peter Day,[8] 104–05.)

In brief, the exchange of concepts with Faraday opened Maxwell's mind to an approach to the problem that would have been beyond Faraday's capabilities, namely expressing the known laws of electromagnetism in the form of three-dimensional field equations and analyzing the result with all appropriate mathematics available at the time. Granting Maxwell's special abilities, Faraday must be given great credit for introducing the concept of a force field. It has found an enduring and increasingly complex place in physics. In searching for mathematical tools, Maxwell was helped by his friend Guthrie Tait (Fig. 13), who was preparing a treatise on a condensed form of vector algebra bearing the designation *quaternions*, which Maxwell adapted to his own needs.

Four Basic Equations

Maxwell emerged from this endeavor with a complete theory initially, by his preference, expressed in the form of relations between potential functions. Maxwell's version was later rewritten by Heaviside in the form of the field equations we today call Maxwell's equations. Two of the equations were generalizations of the laws that were valid for static electric and magnetic systems. One of the other two provided a mathematical description of the laws governing magnetic induction, that is, the generation of an electric field by a changing magnetic field.

The fourth equation deserves special mention since its final form reflected the special insights associated with Maxwell's genius. In part it provided a description of Ampère's law concerning the magnetic field associated with an electric current. Maxwell decided intuitively, and presumably for esthetic reasons associated with a desire for symmetry in the system of equations, that it should also contain a term representing an effect complementary to magnetic induction, namely the generation of a magnetic field by a changing electric field. No such effect had been observed experimentally as yet. However, Maxwell's numerical estimates indicated that an experimental demonstration would be just within the limits of feasibility using available equipment. In particular he suggested (see Maxwell as cited in n. 7; 2: 415) that it should be detectable for electrostatic fields of a magnitude near the breakdown point for air if one employed charged bodies moving at a hundred

FIGURE 13. Peter Guthrie Tait during his most productive years and while a professor at the University of Edinburgh, where he spent most of his career. He and Maxwell, having similar interests in mathematics and physics, had become friends at the Edinburgh Institute, their secondary school. The friendship remained close throughout Maxwell's lifetime, particularly at the professional level. Maxwell found modifications of Tait's mathematical developments in the field of quaternions, a form of vector analysis, particularly useful in formulating the equations of electromagnetic theory. (Courtesy of the library staff of St. Andrews University.)

meters per second. Nevertheless, Maxwell proceeded with confidence without such confirmation. It may be added that direct measurements of Maxwell's extra term were first made in 1875 by the American physicist Henry Rowland while a guest in Helmholtz's laboratory. He had to repeat the experiment twice in the United States to convince skeptics.

The equations recognized that quantities such as the electric currents and electric and magnetic fields could have different directions as well as magnitudes at different points in three-dimensional space. In other words they were expressed in so-called three-dimensional vector form. In the process of developing the theory, Maxwell demonstrated, as mentioned above, that the solutions to the equations could be related to special potential functions, including one of vector form linked to the magnetic field. It is noteworthy that Maxwell preferred to work with the potentials rather than the equations describing the interrelation of the electric and magnetic fields, a practice that has found its place in modern field theory. J. J. Thomson, who edited the third edition of Maxwell's *Treatise*, placed more emphasis on the latter in his own version of the work.[7] Much of the notation Maxwell introduced in the course of his analysis remains in use at the present time.

Maxwell had long been interested in the effects that electromagnetic fields could produce on materials. For example, surface layers of electric charge having opposite sign could be induced on opposite sides of insulating films by applying an electric field perpendicular to the surface (electric polarization). In a similar vein, some materials, such as iron, could enhance the strength of an applied magnetic field. Maxwell left room to include such effects in the framework he developed. He understood with complete clarity, however, that many of the questions he raised in exploring matters of this kind could not be treated adequately until one had much fuller knowledge of the laws governing atomic systems. Indeed, many ultimately required the use of the form of quantum mechanics developed in the 1920s. He also struggled in vain to fit the phenomenon of gravitation into the system of fields he had developed. Nevertheless, Maxwell remained committed to the continuous development of the theoretical framework until his death.

Electromagnetic Theory of Light

All physical quantities can be related to the three fundamental measurable parameters: length, time, and mass. The combination of the three that is appropriate for any given physical quantity is commonly referred to as its "dimensions." For example, the dimension associated with speed or velocity is length divided by time, whereas that for acceleration, the rate of change of velocity, is length divided by time to the second power. This principle had been noted and used earlier by the mathematician Gauss. Maxwell, however, appears to have been the first individual to use it consistently in his work in order to keep his equations in balance since the dimensions of all terms in an equation should be the same. Maxwell's practice became standard within the profession.

In the course of his work, Maxwell noted that the constant giving the ratio between the two different scales that had been introduced in early studies of static electricity and magnetism (see pp. 23–24) had the dimensions of velocity. Moreover, his equations possessed solutions describing transversely polarized electromagnetic waves that traveled in free-space with that velocity. Examination of the then fairly crudely known values of the constant (accurate to about 2 percent) demonstrated that they were in the range of the comparably crude known values of the velocity of light. This immediately stimulated new, somewhat more precise, measurements of the constants that removed any doubt that the two are the same. Maxwell joyfully announced the electromagnetic theory of light in 1863. He did not hesitate to use the term "ether waves" in popular discussions at this stage.

It should be emphasized that the addition Maxwell had made to the fourth of his equations, mentioned above, was essential in providing support for his electromagnetic theory of light.

Maxwell, incidentally, developed one of the more accurate methods of determining the ratio of the two systems of electromagnetic units. It involved a torsion balance in which the null state was achieved when the repulsive force of two similarly charged discs balanced the repulsive force of two opposed electromagnets (see Fig. 14).

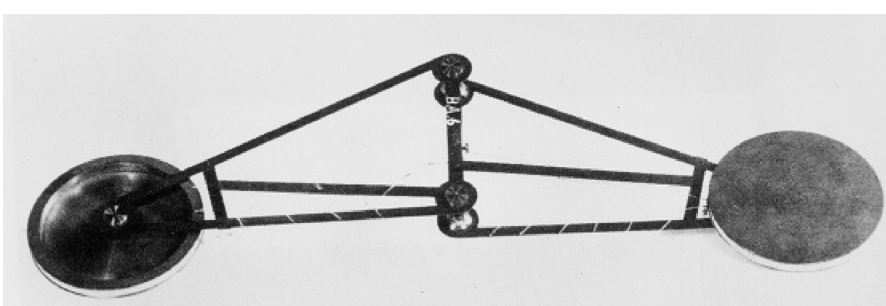

FIGURE 14. An oblique view of the mounted balance pans employed by Maxwell in his determination of the ratio of the electrostatic and magnetic units. In the experiment, the framework was suspended so that the planes of the disks were vertical and free to oscillate horizontally about a torsion suspension wire attached to the central bar of the frame (note mounting button for suspension). One disk, bearing an electric charge, was in close proximity to a similar fixed disk having the same, repellant, charge. The other disk, bearing an electromagnet, was in similar close proximity to a fixed electromagnetic coil possessing a repelling magnetic field. The magnetic fields were varied until a torsion-free point was reached and the effects of the two types of fields were equal. The ratio of electrostatic and magnetic units, which possesses the dimensions of velocity, turned out to be the same as the known velocity of light within experimental errors, supporting Maxwell's proposal that light waves are electromagnetic in nature. (Courtesy of C.W.F. Everitt; n. 3.)

Hermann Helmholtz and Heinrich Hertz

Hermann Helmholtz noted Maxwell's papers on the subject and ultimately succeeded in urging his former best student, Heinrich Hertz, to see if he could produce such electromagnetic waves with normal laboratory electrical equipment. Unfortunately, Maxwell was no longer alive when Hertz announced his own success in the second half of the 1880s. Actually, Maxwell did realize toward the end of his life that electricity would come to play a major role in human affairs. A strong interest in practical applications involving motors, transformers, and electrical illumination had emerged by 1879.

Departure from London; "Retirement"

Although Maxwell enjoyed many aspects of the life in London during his five years at King's College (1860–65), including a close association with Faraday, the academic burdens were relatively heavy, leaving him no more than marginal time for the research he loved. Finally he decided during a bout of illness (erysipelas) to give up academic life and settle in at Glenlair, where he already had facilities for experimental research that could readily be expanded to suit his needs. His many admiring friends in Scotland urged him to accept a university post there that would give him much more freedom than he had in London. He expressed profound gratitude to them and to the individuals who actually arranged the offers, but ultimately declined. He wished to spend as much of his remaining career as he could on research, particularly that dealing with the electromagnetic world. The photograph of Maxwell shown in Figure 15 was taken at about this time.

After his death, a rumor developed that Maxwell had been requested to resign from King's College because he could not control the unruly students in some of his classes. This rumor is absurd on the face of it since Maxwell's five years at the college were among the most productive in his life and were those in which he gained great international fame, granting that he was probably much more effective in dealing with advanced students who were dedicated to a professional career in natural philosophy than with those having other goals. Maxwell was indeed "the brightest gem in the crown" of King's College. C. Domb, a member of the Royal Society of London who has devoted a valuable paper[4] to this and other issues concerning Maxwell's five years in London, has obtained convincing evidence that the rumor is entirely false. For one thing, Maxwell offered to stay on for a year if there was a delay in finding a successor. Maxwell left because he wanted more free time for research and the good life at Glenlair.

Incidentally, Domb also discusses some of Maxwell's relationships

FIGURE 15. A photograph of Maxwell taken in his mid-thirties, about the time he departed from King's College London and was at the height of his career. (Courtesy of C.W.F. Everitt and Peterhouse, Cambridge University.)

with St. Andrews College after leaving London. His good friend Lewis Campbell was most anxious to have him there as an associate occupying a chair bearing special honors as a gift of the Crown and linked to a light teaching load since he would serve as principal. Initially, Maxwell was moderately responsive to the proposal but the plan was finally dropped by mutual agreement. In one of his letters to a friend at Aberdeen, Maxwell comments: "One great objection is the East Wind which I believe is severe in those parts."

It is interesting that the national political preferences of the candidate were taken into account in filling such a special chair. Apparently the concept of "political correctness" is not entirely new in the academic world. One is reminded of King George's decision that the lightning rods installed in England should have ball tips rather than pointed ones as Benjamin Franklin, the inventor of the rods, recommended. The king detested Franklin for insisting that the American colonists be treated on the same basis as English citizens. Incidentally, Maxwell appears to have been completely oblivious to the political issues of his day. Campbell's sensitivity to the political climate at his college was such that he later denied (perhaps falsely) that he had initiated the proposal that Maxwell occupy the special chair.

Examiner of the Tripos

Nevertheless, Maxwell eventually accepted two posts that he may have felt he could not refuse as a matter of principle, while admitting that he would enjoy a continuing link to the academic world. First, he agreed to serve as examiner of the tripos examinations at Cambridge for four years (1866–68 and 1869–71). The action came in spurts that did not interfere continuously with his other interests. It also gave him an opportunity to insert mathematical problems that had some bearing on the physical world but did not diminish mathematical standards.

The Cavendish Laboratory

In 1871, the senate of Cambridge University decided to establish an experimental laboratory to be named after the duke of Devonshire, who had offered to fund its construction the previous year. A member of the Cavendish family, he was serving as chancellor of the university at the time.

Maxwell was not the first individual to be asked to serve as the guiding professor for the development of the new laboratory, although he was undoubtedly much interested in the project. In fact, among several others, it was previously offered to Helmholtz. Maxwell accepted it in 1871, presumably after much persuasion and careful thought, when finally asked. The concept and his emotional attachment to the university lay too deep in his heart for refusal. After some review, he and the chancellor finally decided that the building should most properly be named after the physicist Henry Cavendish (1731–1810). Henry Cavendish was distinguished, among other things, for making one of the first accurate measurements of the constant determining gravitational

FIGURE 16. The façade of the original Cavendish Laboratory constructed under Maxwell's direction and opened in 1874. It housed some of the most brilliant discoveries in physics made in modern times. It is no longer a physics laboratory, having been replaced in 1974 by a more modern laboratory situated in the suburbs. (Personal photograph.)

attraction. He was also the first to declare the status of a primary chemical element in the modern sense, namely hydrogen.

Maxwell spent much time in the detailed design of the beautiful building (Fig. 16), borrowing information gained from successful laboratories elsewhere and adding many items that emerged from his own significant experience. It was destined to become a world-class center of research, not least during the era in which Ernest Rutherford, who led the way toward unraveling the secrets of the atomic nucleus, directed it. Although the building was completed by 1874 and immediately put to use, another three years were required before it was fully furnished with equipment and other facilities. The chancellor provided much of the money for this, but Maxwell added many items he considered essential at his own expense. He remained the professor at the laboratory until his death in 1879. Significant amounts of his later work, including the second edition of a two-volume treatise on electromagnetism,[7] were published posthumously.

Questions of Relativity

Even before Maxwell's death, there was open discussion whether Maxwell's equations conformed to Galileo's principle that the equations of physics should be identical in two reference frames that move with constant velocity relative to one another. Galileo's classical example involved two ships that are on parallel courses and moving with uniform speeds in opposite directions. The topic was highly pertinent since Maxwell had introduced the concept that a moving electric charge carries a magnetic field with it. What would occur if you decided to move along with the charge and how did the concept of the ether fit into the picture? The attempts by A. A. Michelson and E. W. Morley, and others, in the 1880s, to detect the motion of the earth relative to the ether, had led to negative results, heightening the importance of the issue. Many individuals joined the discussion, but it will serve our purpose to focus on the views of three, namely H. A. Lorentz (1853–1928), E. Poincaré (1859–1912), and A. Einstein (1879–1955). Their investigations are discussed in elegant detail in the earlier pages of A. Pais's biography of Einstein.[9]

Lorentz had distinguished himself early in his career by proposing the existence of electrons in atomic systems well before they were discovered in experiments with cathode ray tubes. He was guided by studies of the variations in refractive index in systems such as crystals as a function of the wavelength of light and the assumption that electrons act as elastically bound charges. Once their existence was confirmed more directly by cathode ray experiments, he focused activity on theoretical investigations of their properties. Much of his own work of the period is reviewed in detail in a book he published in 1906, based on a series of lectures given at Columbia University in the spring of 1906.[10]

If we select a year such as 1904 as a significant milepost, it seems reasonable to state that Lorentz held the following opinions: The ether is probably real, all-pervasive, and fixed in space. Time is universal. The failure to detect motion relative to the ether occurs because matter, including measuring equipment, contracts in the direction of motion in such a way as to mask motion relative to the fixed ether, a hypothesis proposed independently by G. F. Fitzgerald.

It should be added that as a working mathematical physicist, Lorentz was much interested in developing mathematical tools that could simplify finding solutions to equations. Solutions to Maxwell's equation were no exception. He noted in 1904[11] that the form of the equations remained unchanged if the three spatial coordinates, usually designated x, y, and z, and the time coordinate, t, were altered simultaneously in a way that was equivalent to a change in velocity of the system under study. The new transformed coordinates might, for example, be designated x', y', z', and t'. Thus, in a purely mathematical sense, one could treat an electromagnetic system, such as a single electric charge moving with uniform velocity v, as though it had a different velocity v', solve the equations in the new frame of reference if there was advantage in doing so, and then *transform* the solution back to the original frame. Or, starting with a simple spherical charge at rest one could track the change in the electromagnetic field accompanying the charge from stage to stage mathematically as it acquires velocity on a linear course. The Lorentz-Fitzgerald contraction of the field in the direction of motion emerges in the process in what might be termed a dynamic manner.

The mathematical technique and the equations involved were soon designated the *Lorentz Transformation* and the *Lorentz Equations*. It should be emphasized that as far as Lorentz was concerned in 1904, the changes in time scale employed in the process were purely fictitious, having mathematical and not physical significance.

Poincaré, in addition to being a brilliant mathematician, had very broad interests in many related areas, including logic, the philosophical implications of mathematics, and, not least, the application of mathematics to classical as well as forefront physical problems. Thus he struggled with the problem of three bodies that interact with one another through Newtonian gravitational forces and entered wholeheartedly into the discussion of the conditions that should extend the classical Galilean concept of relativity with the introduction of Maxwell's equations. It seems safe to say that in 1904 he had diminishing belief in the existence of the ether as commonly understood at the time and thought that the solution to the problem lay within the mathematical structure of Maxwell's equations, which he, like Lorentz, tended to treat in a dynamic manner. Being a highly accomplished mathematician, he was able to draw more complete information from the mathematical structure of the Lorentz transformation than Lorentz had.[12] He did mention that the modified time parameters going with the various states linked by the Lorentz transformation can be regarded as equally real, but apparently based his statement on a mathematical-philosophical perspective rather than a physical one. He also mentioned that the velocity of light should be the same for all observers. He was getting close to resolving the issue, but clearly was not yet prepared to take the leap necessary to attain a final solution. Nor was it obvious that he would do so with all the revolutionary physical implications involved.

It is precisely at this point that the hitherto essentially unknown Einstein displayed his remarkable genius and resolved the problem. He was then twenty-seven years old and had been working in the Swiss patent office as an analyst of complex technical patents. Essentially independent of Poincaré, he reached the same level of understanding of the properties of the Lorentz transformation, but realized that the solution to the problem at hand lay in a geometrical, or kinematic, interpretation of the transformation. In brief, it was necessary to set aside the concept of universal time and conclude that the time changes involved in the transformation equations were not fictitious, as Lorentz assumed, but were expressions of reality: *Time is Relative*. If an observer takes note of a clock identical to his own, which is moving at a uniform rate relative to him, he will find that it is keeping time more slowly than his, and precisely in accordance with Lorentz's equations. At the core of Einstein's approach to the problem was a view he had apparently held since student days, namely, that the velocity of light was probably the same for all observers.

In the first edition of Lorentz's book on the electron (1906), he confesses that the implications of Einstein's conjectures were too radical for him to absorb rapidly. The notes in the reprinted version of 1923 contain expressions of regret that he had been so slow in appreciating the gigantic step the young Einstein had taken. He also notes that the physicist W. Voigt had preceded him in developing the Lorentz transformation in a study[13] of the Doppler effect as measured by an observer moving relative to the source at speeds near the velocity of propagation of waves.

Poincaré was perhaps somewhat disappointed that he had lacked the boldness to take the great leap, but eventually wrote a glowing tribute to Einstein's very special gifts and continued to follow the course of advances in forefront physics as it struggled onward with the quantum world.

The Shoulders of Maxwell

When it was widely realized in the years immediately after World War I that a scientist of the stature of Isaac Newton, namely Albert Einstein, had emerged in continental Europe, the English press comforted the population with the statement, "After all, he stood on Newton's shoulders!" Soon after, when Einstein visited England for the first time following the war, a group of reporters surrounding him asked him if he felt the statement was valid. He responded with his special gift of sly humor: "The statement is not quite right. I stood on Maxwell's shoulders!" One may indeed wonder what Maxwell's responses to Einstein's 1905 papers on special relativity, Brownian motion, and the quantization of light waves would have been if he had had the good fortune to live another thirty years with fully retained acuity. As matters stood in 1879, Maxwell knew that he had constructed major bridges to the future, but could only speculate about the nature of the land that lay beyond.

Notes

1. See the small volume of lectures by P. G. Harman, *The Natural Philosophy of James Clerk Maxwell* (Cambridge University Press, 1998), 12. Professor Harman is also preparing a three-volume edition of the letters and papers of Maxwell: *The Scientific Letters and Papers of James Clerk Maxwell.* Two volumes have appeared to date (Cambridge University Press, 1990, 1995).
2. In preparing this biography, I have received much guidance from two sources: First, the six-hundred-page biography by Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (New York: Johnson Reprint Corporation, 1969). This is a reprint of the first edition, London, 1882, with a selection of letters from the second edition of 1884, edited by Robert H. Kargon. As noted in the text, William Garnett admired Maxwell so much that he named his son James Clerk Maxwell Garnett. Second, Professor C.W.F. Everitt of Stanford University, who has written many essays dealing with the life and times of Maxwell, generously made a careful reading of an advanced version of this article and made numerous valuable comments and suggestions, which have been incorporated in the present version. Some of his contributions relate to correcting errors, others to important refinements of detail. A list of some of his own extensive writings is given in n. 3.
3. C.W.F. Everitt, *James Clerk Maxwell* (New York: Charles Scribner's Sons, 1975). This small, highly readable book concentrates for the most part on Maxwell's scientific work. It throws a great deal of light on his minor as well as major pursuits. It also contains a number of interesting photographs and a useful bibliography. Professor Everitt has also written eloquent and insightful essays concerning Maxwell and his work that appear in the following sources: *Macmillan Encyclopedia of Philosophy*, ed. Paul Edwards (Macmillan Press, first volume 1967); *Springs of Scientific Creativity*, ed. Rutherford Aris, Roger H. Stuewer, and H. Ted Davis (University of Minnesota Press, 1983); *Routledge Encyclopedia of Philosophy*, ed. Luciano Floridi and Edward Craig (Routledge Press, first volume 1998). The essay appearing in *Springs of Scientific Creativity* is particularly noteworthy for its depth of analysis of Maxwell, his ancestral background, his times, and his research. The book is unfortunately out of print. I am indebted to Professor Stuewer for his remaining spare copy.

   I am also deeply indebted to Professor Everitt for permission to copy some of the photographs in his book. Acknowledgment is given in each case.
4. C. Domb, *James Clerk Maxwell in London (1860–1865)*, Notes and Records of The Royal Society of London 35.1 (July 1980).
5. Thomas Young had one of the most creative minds of his era. Although trained as a physician, a profession he practiced sporadically, he had many side activities related to science. For example, he became convinced that Newton's version of the

corpuscular theory of light was incorrect and waged, successfully, an uphill struggle to demonstrate that light possessed wave characteristics. His work inspired much brilliant research in France. Young is also credited with some of the first successful translations of the Egyptian text on the Rosetta Stone, which contained both Greek and Egyptian versions of the same document.

6. See, for example, Joseph Larmor, *Aether and Matter* (Cambridge University Press, 1900). This was published just before Albert Einstein introduced the special theory of relativity (1905). The latter resolved some of the issues regarding measurements made on bodies possessing relative motion that concerned Larmor and his colleagues. Major problems with respect to the precise physical nature of the vacuum remain with us, however, ever since Dirac's development of a relativistic theory of the electron involving negative energy states and Carl Anderson's discovery of the positive electron. See also Edmund T. Whittaker, *A History of the Theories of Aether and Electricity* (New York: Dover Publications, 1989). Longmans, Green and Company, London, published a first edition of Whittaker's book in 1910.
7. James Clerk Maxwell, *A Treatise on Electricity and Magnetism, Volumes 1 and 2* (New York: Dover Publications, Inc., 1954). This is an unabridged, slightly altered, republication of the third edition, published by the Clarendon Press in 1891. The first edition was published in 1873, the second posthumously in 1881. J. J. Thomson supervised the third edition.
8. John Meurig Thomas, *Michael Faraday and the Royal Institution* (Bristol and Philadelphia: Institute of Physics, Ltd., 1997); Peter Day, comp., *The Philosopher's Tree; Michael Faraday's life and work in his own words* (Bristol and Philadelphia: Institute of Physics, Ltd., 1999).
9. Abraham Pais, *"Subtle is the Lord"* (Oxford University Press, 1982).
10. H. A. Lorentz, *The Theory of Electrons* (New York: G. P. Stechert and Company, 1906; reprinted with editorial comments in 1923).
11. H. A. Lorentz, "Electromagnetic Phenomena in a System Moving with any Velocity Less than that of Light," *Proceedings of the Academy of Sciences of Amsterdam*, 1904, p. 6. The analysis contained in this paper is repeated in *The Theory of Electrons.*
12. H. Poincaré, *C. R. Ac. Sci. Paris* 140 (1905), 1504; *Rend. Circ. Mat. Palermo* 21 (1906), 129.
13. W. Voigt, "Ueber das Doppler'sche Princip," *Nachrichten Universität zu Göttingen*, 1887, p. 41. It is not known if this paper was stimulated by considerations derived from the form of Maxwell's equations. Voigt is best known for his extensive studies of the physical properties of crystals summarized in his encyclopedic volume *Lehrbuch der Kristalphysik* (Leipzig: Teubner, 1928). This is a second edition with additions by M. von Laue (courtesy of the APS Library).

Additional References

W. D. Niven, *The Scientific Papers of James Clerk Maxwell*, 2 vols. (Cambridge University Press, 1890).

Jed Z. Buchwald, *The Rise of the Wave Theory of Light: Optical Theory and Experiment in the Early Nineteenth Century* (University of Chicago Press, 1995); *From Maxwell to Microphysics: Aspects of Electromagnetic Theory in the last Quarter of the Nineteenth Century* (University of Chicago Press, 1985).

Appendix A

The Reverend Lewis Campbell's analysis of the personal characteristics of Maxwell. This is taken from the biography written by Campbell and Garnett, 425–33. The footnotes in Campbell's statement are also given here.

> In these reminiscences I have purposely abstained as much as possible from comment. But in concluding this portion of the present work, I may be permitted to record a very few general observations or impressions.
>
> The leading note of Maxwell's character is a grand simplicity. But in attempting to analyse it we find a complex of qualities which exist separately in smaller men. Extraordinary gentleness is combined with keen penetration, wonderful activity with a no less wonderful repose, personal humility and modesty with intellectual scorn. His deep reserve in common intercourse was commensurate with the fulness of his occasional outpourings to those he loved. His tenderness for all living things was deep and instinctive; from earliest childhood he could not hurt a fly. Not less instinctive was the sense of equality amongst all human beings, which underlay the plainness of his address. But, on the other hand, his respect for the actual order of the world and for the wisdom of the past, was at least as steadfast as his faith in progress. While fearless in speculation, he was strongly conservative in practice.
>
> In his intellectual faculties there was also a balance of powers which are often opposed. His imagination was in the highest sense concrete, grasping the actual reality, and not only the relations of things. No one was ever more impatient of mere abstractions.[1]
>
> Yet few have had so firm a hold upon ideas. Once more, while he was continually striving to reduce to greater definiteness men's conceptions of leading physical laws, he seemed habitually to live in a sort of mystical communion with the infinite.
>
> His aunt, Mrs. Wedderburn, who had had the care of him during so much of his early life, said on the occasion of his marriage, "James has lived hitherto at the gate of heaven."
>
> Mr. Colin Mackenzie has repeated to me two sayings of his during those last days, which may be repeated here—"Old chap, I have read up many queer religions: there is nothing like the old thing after all;" and—"I have looked into most philosophical systems, and I have seen that none will work without a God."
>
> Maxwell's humour, which with many passed for mere eccentricity, and to some was the characteristic by which he was chiefly known, at least in earlier life, may be passed over lightly here. With strangers it

[1] He was particularly indignant at the confusion caused by some would-be philosophers of *facts* and *laws*.

was sometimes the veil of a sensitiveness which but for this would have made him the victim of his immediate surroundings. In confidential intercourse it was a perpetual fund of delight, the vehicle of his immediate surroundings as it glanced in all directions from the immediate topic of discourse.

It was his way of acknowledging "the grotesque view"[2] of everything. Like other humourists whom I have known, he was never tired of a joke which had once tickled him; only, if retained in employment, it must always be tricked out with some new livery, and have some fresh turn given to it. As late as the summer of 1879, in writing to Professor Baynes about an article on Chemistry for the *Encyclopedia Britannica*, he repeated in some new way the well-worn jest about "an Analyser or a Charlatan." Even on his deathbed at Cambridge, in familiar converse with his cousin and friend, Mr. Colin Mackenzie, he still used the old quaint familiar speech:—"No, not that phial! The little red-headed chap!"

Nor is it necessary to dwell on the rare freshness of feeling which he carried into middle life. The reader of his correspondence at any period must feel involuntarily that he had "the dew of his youth."

In thinking of him in college days, I used often to associate him in my own mind with Socrates. There is one point in the resemblance which I had not then realised, the "Socratic strength" of Antisthenes—his extraordinary power of moral and physical endurance.—Once at Cambridge, when his wife was lying ill in her room, and a terrier, who had already shown "a wild trick of his ancestors," was watching beside the bed, Maxwell happened to go in for the purpose of moving her. The dog sprang at him and fastened on his nose. In order not to disturb Mrs. Maxwell, he went out quietly, holding his arm beneath the creature, which was still hanging to his face.

What had struck me, I suppose, in making the above comparison, was the eager spirit of inquiry beneath the ironical shell. I might have added the union of speculation with mysticism, and of conservatism with progressive thought. But in one essential point, the dialectical cross-questioning method, the analogy fails. For Maxwell had not spent his youth in the Athenian agora, but in the solitudes of Galloway, where he had interrogated Nature more than Man.

In his conversation he might rather be compared with the earlier Greek thinkers, "who," says Plato, (Soph. 243 B) "went on their several ways, without caring whether they took us with them, or left us behind." The necessity of utterance was often stronger with him than the endeavour to make himself understood, and he would pour out his ideas in simple affectionateness to those who could not follow them. His thoughts were often tentative, but his expression of them

[2] P. 262 of Campbell and Garnett.

was always dogmatic, even in the negative formula “No one knows what is meant by” so and so.

His indirect, allusive way of speaking was not, however, wilfully assumed, but was the result of idiosyncrasy and early habit; and it disappeared utterly in the presence of any great occasion—a great joy, a great sorrow, or a great duty. Then his speech resolved itself into statements of fact, brief and unemotional, but absolutely simple and direct. And, latterly at all events, such were generally the characteristics of his style in writing. I have been told by Mr. Huddelstone, a late Fellow of King’s College, Cambridge, that when consulted about a lightning conductor for King’s College Chapel (a building which he greatly loved) Maxwell called and made a verbal explanation which was unintelligible, but in going away he fortunately left a written statement, and this was perfectly clear.

The Galloway boy was in many ways the father of the Cambridge man; and even the “ploys” of his childhood contained a germ of his life-work. Indeed, it may be said that with him, despite the popular adage, “Work when you work,” play was always passing into work and work into play. In twirling his magic discs, his mind was already busied about the cause of optical phenomena. He plied the devil-on-two-sticks with the same eager industry, and with the same simple enjoyment, with which he afterwards spun his dynamical top. And amidst his profoundest investigations, whether about the Rings of Saturn or the Lines of Force, or the molecular structure of material things, the playful spirit of his boyhood was ever ready to break forth. Meanwhile, alike beneath the grave and sparkling mood, a spirit of deep PIETY pervaded all he did, whether in the most private relations of life, or in his position as an appointed teacher and investigator, or in his philosophic contemplation of the universe. There is no attribute from which the thought of him is more inseparable.

He had keen sympathy with ideal aspirations, together with an occasional sense of their fruitlessness. “It’s no use thinking of the chap ye might have been.” When, in their early married life, Mrs. Maxwell was oppressed with a sense of failure in her first attempts at Cottage-visiting, he made her sit down while he read to her Milton’s sonnet ending with the line, “They also serve, who only stand and wait.”

He appears in early days to have been conscious of some superficial weaknesses, of a certain excitability of temperament, leading to “preconscious states” and preventing him from at once setting himself right in new surroundings; also of the equal danger of shrinking into himself, and “mystifying” those about him. This difficulty, and many others “within and without,” he overcame. But it would be too much to say of him that “his affections never swayed more than his reason,” or that he obtained as firm a foothold in practical life as he had by birthright in the region of scientific thought. This great mass of mind was so delicately hung as to be guided sometimes by a silken thread. Few men, if any, would venture to argue or remonstrate with Maxwell when he had decided on a course of action in the council-chamber of his own breast. But he could not consciously hurt any creature, nor permit the possibility of causing pain to those he loved. Nor was his power over others always adequate to the keenness of his perceptions. For while his penetration often reached the secrets of the heart, his generosity sometimes overlooked the most obvious characteristics—especially in the shape of mean or vulgar motives.

His liberality, in every sense of the word, was absolute. People have been disposed to criticise the plainness of his entertainments, without knowing that while this was a matter of taste, the difference between the plain and the luxurious table was uniformly dispensed in charity. He has also been supposed by some who think that science should disown religion, to have been intolerant as well as orthodox. The contrary was true. And in particular, the mutual admiration and regard for one another of two such men as Maxwell and Clifford, notwithstanding their profound divergence of opinion on subjects of human interest, deserves to be quoted as an honourable exception to the narrow exclusiveness which has been too prevalent alike in the Christian and the anti-Christian world.[3]

He never sought for fame, but with sacred devotion continued in mature life the labours which had been his spontaneous delight in boyhood. Yet, considering the high region in which he worked, he received a large measure of recognition even in his lifetime. The Rumford Medal, conferred in 1860, was the first of a long list of honours, which up to his last year continued to accumulate from all parts of the civilised world.[4] And some of those who had an eye for genius, though their intellectual interests lay in different spheres from his, could not forbear their testimony. Out of many such expressions it is enough to have selected one. Mr. Frederick Pollock in his work on Spinoza, having occasion to refer to Maxwell's views on matter and space, adds the following note (p.115):—

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[3] About the year 1860 I remember discussing with him J. Macleod Campbell's book on the Atonement, which had lately appeared. He made some criticisms, which I have forgotten, but I remember the emphatic tone with which he said, "We want light."

[4] In 1870 Maxwell received the honorary degree of LL.D. in the University of Edinburgh; on 11th November 1874 he was elected Foreign Honorary Member of the American Academy of Arts and Sciences of Boston; on 25th October 1875, Member of the American Philosophical Society of Philadelphia; on 4th of December 1875, Corresponding Member of the Royal Society of Sciences of Göttingen; on 21st of June 1876 he received the honorary degree of D.C.L. at Oxford; on 5th December 1876 he was elected Honorary Member of the New York Academy of Sciences; on 27th of April 1877, Member of the Royal Academy of Science of Amsterdam; on 18th August 1877, Foreign Corresponding Member in the Mathematico-Natural-Science Class of the Imperial Academy of Sciences of Vienna; and in the spring of 1878 he received the Volta Medal and degree of Doctor of Physical Science *honoris causa* in the University of Pavia.

Clerk Maxwell was living when these lines were written: I cannot let them pass through the press without adding a word of tribute to a man of profound and original genius, too early lost to England and to Science.

Great as was the range and depth of Maxwell's powers, that which is still more remarkable is the unity of his nature and of his life. This unity came not from circumstance, for there were breaks in his outward career, but from the native strength of the spirit that was in him. In the eyes of those who knew him best, the whole man gained in beauty year by year. As son, friend, lover, husband; in science, in society, in religion; whether buried in retirement or immersed in business—he is absolutely single-hearted. This is true of his mental as well as of his emotional being, for indeed they were inseparably blended. And the fixity of his devotion both to persons and ideas was compatible with all but universal sympathies and the most fearless openness of thought. There are no "water-tight compartments,"[5] there is no "tabooed ground,"[6] in spite of much natural reserve, he never really lost his predilection for "a thorough draft."[7] That marvellous interpenetration of scientific industry, philosophic insight, poetic feeling and imagination, and overflowing humour, was closely related to the profound *sincerity* which, after all is said, is the truest sign alike of his genius and of his inmost nature, and is most apt to make his life instructive beyond the limits of the scientific world. He would not wish to be set up as an authority on subjects (such as historical criticism) which, however interesting to him, he had not had leisure to study exhaustively. But our age has much to learn from his example. And in his life, regarded as a whole, there is a depth of goodness which can be but faintly indicated in his biography.

Appendix B

Text of a letter from Michael Faraday to the Reverend E. Jones in Kent in response to one he had received from Jones on a scientific issue. The letter dates from 1857, when Faraday was sixty-six years of age. (Courtesy of Professor Peter Day.)

The cases of action at a distance[8] are becoming, in a physical point of view, daily more and more important. Sound, light, electricity, magne-

[5] P. 205.

[6] P. 179.

[7] See the occasional poem on St. David's Day.

[8] Here Faraday uses "action at a distance" in his own special sense as any action in which activity at one point can produce an effect elsewhere. The effect need not be simultaneous but could, for example, be produced by a wave having a finite velocity. In Newton's treatment of planetary motion, the force of gravity was assumed to be instantaneous, an assumption that was effective because the velocities of the planets are small compared to the speed of light, Mercury providing a slight exception. Einstein's general theory of relativity permits

> tism, gravitation, present them as a series. The nature of sound, and its dependence on a medium, we think we understand pretty well. The nature of light as dependent on a medium is now very largely accepted. The presence of a medium in the phenomena of electricity and magnetism becomes more and more probable daily. We employ ourselves, and I think rightly, in endeavouring to elucidate the physical exercise of these forces, or their sets of antecedents and consequents, and surely no one can find fault with the labours which eminent men have entered upon in respect of light, or into which they may enter as regards electricity and magnetism. Then what is there about gravitation that should exclude it from consideration also? Newton did not shut out the physical view, but had evidently thought deeply of it, and if he thought of it, why should not we, in these advanced days, do so too? Yet how can we do so if the present definition of the force, as I understand it, is allowed to remain undisturbed? Or how are its inconsistencies or deficiencies as a description of the force to be made manifest, except by such questions and observations as those made by me, and referred to in the last pages of your paper? I believe we ought to search out any deficiency or inconsistency in the sense conveyed by the received form of words, that we may increase our real knowledge, striking out or limiting what is vague. I believe that men of science will be glad to do so, and will even, as regards gravity, amend its description, if they see it is wrong. You have, I think, done so to a large extent in your manuscript, and I trust (and know) that others have done so also. That I may be largely wrong I am free to admit—who can be right altogether in physical science, which is essentially progressive and corrective? Still, if in our advance we find that a view hitherto accepted is not sufficient for the coming development, we ought, I think (even though we risk something on our own part), to run before and rise up difficulties, that we may learn how to solve them truly. To leave them untouched, hanging as dead weights upon our thoughts, or to respect or preserve their existence whilst they interfere with the truth of physical action, is to rest content with darkness and to worship an idol.

Acknowledgments

Many individuals have contributed to the development of this paper, not least Dr. Alexander G. Bearn, executive officer, and Ms. LeFaivre-

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treatment of gravitational problems in which gravitational forces are much larger than those to which Newton applied his theory and in which the velocities of material bodies are close to that of light. The theory also predicts the possible generation of gravitational waves. Waves generated in outer space are being sought with earth-mounted equipment but have not yet been observed. A recent study of the motion of the components of a special double star system leaves little doubt, however, that the generation of such waves accounts for dissipation of the energy of motion of the components of that system.

Rochester, editor, and her staff, at the American Philosophical Society. Friends in Cambridge, England, provided similar help and guidance. Foremost with respect to details were Professor Brian Pippard, who was director of the Cavendish Laboratory between 1971 and 1982, when it was moved to new quarters in the suburbs of Cambridge, and Professor C.W.F. Everitt of Stanford University, cited in n. 2. Among many other attributes, both individuals possess a thorough knowledge of the work of Maxwell and the lore surrounding the latter's activities. Having gained much useful information from Everitt's small book on Maxwell (n. 3), I was delighted to learn that he had continued on the faculty of Stanford University and was most willing to exchange correspondence. In this connection, he shared some of his eloquent writings about Maxwell that appeared in collections of essays. He also allowed me to make copies of photographs that appeared in his book. As noted in note 2, he made a careful reading of a near-final version of my own essay and offered many valuable comments that have been incorporated in the present text. Not least, I am indebted to Pippard for a copy of a book by Professor Peter Day, of the Royal Institution, containing some of the philosophical writings of Michael Faraday (n. 8), who played a critical role at a special point in Maxwell's development of electromagnetic theory.

At Cambridge, I also benefited from discussions with Professor Robert W. Cahn and Alan Cottrell, also emeritus members of the Cavendish and familiar with its history. The former, in company with Dr. Gordon Squire, gave me a guided tour of portions of the new Cavendish Laboratory, including a section devoted to an exhibit of some of the experimental equipment designed and used by Maxwell.

Professor John Meurig Thomas, master of Peterhouse, Cambridge University, and professor of chemistry, the Royal Institution, where Faraday carried on his research, was most generous in giving me additional material related to Faraday and his relationship with Maxwell (n. 8) as well as the privilege to use figure 15.

When he became aware of my interest in the life of Maxwell, Jesse Ausubel, on our own campus, called my attention to the relevant books written by Professor Jed Z. Buchwald (see Additional References).

James S. Koehler, my longtime friend and former colleague at the University of Illinois, offered to undertake a critical reading of the final draft version of the essay. It has benefited much from his comments and related discussion.

Finally I continue to remain deeply indebted to Mrs. Florence Arwade, who manages my office and who served the goals of this work in many, many ways. I am similarly indebted to our university librarian, Ms. Patricia Mackey, for her countless literature searches and other help.