Chapter IV
Maxwell's "Electric Science"

The development of modern physics, which I have tried to portray in outline in the last three chapters, reached a highpoint in the works of Maxwell. To his great contributions to modern physics I would like to devote the last chapter of this book. Yet, before doing so a few introductory remarks will be in order.

Maxwell was an eminent and very productive scientist who made important contributions to several sciences. Just to mention a few of them: work in mathematics, both pure and applied; contributions to the development of The Cavendish Laboratories; his scientific work on Color Vision and modern Color Theory; his work in Statistical Mechanics, etc. In this book I shall not say much about any of these important contributions and limit myself to his contributions to electromagnetic theory, or, to use Maxwell's own words, to "electric science," contributions for which Maxwell is widely known and admired highly.[1]

Maxwell's contributions to electromagnetic theory are extremely difficult to describe and explain without making use of mathematics. Yet I will make an effort to explain Maxwell's ideas without the help of any mathematical formulae. I fully realize, as many others before me have done, that such an effort is virtually doomed to failure, because of the enormous problems such an effort will involve. Yet with Glazebrook,[2] I have become convinced that this attempt must be made, because there are many well-educated people who have adequate knowledge of modern physics to understand electromagnetism, but are unable to follow the often difficult mathematical analyses in Maxwell's own works. By the way, Maxwell himself characterized the mathematics he was going to use as "most intricate," and very difficult. I shall return to this shortly.[3]

In addition, my treatment of his contributions to this immense field is very incomplete. I must limit myself to what I take to be essential for the main point I try to make here, namely to show the interpretive nature of modern science.

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[1] Cf. *Enc. Brit.*, 1967 edition, vol. 15, pp. 3–4.

[2] R.T. Glazebrook, *James Clerk Maxwell and Modern Physics* (New York: MacMillan, 1869), Preface, p. *v*.

[3] *The Scientific Papers of James Clerk Maxwell.*, ed. W.D. Niven, 2 vols. (Cambridge: Cambridge University Press, 1890), vol. 1, p. 155.

Article 1. James Clerk Maxwell (1831-1879): Formative Years[4]

James was born in Edinburgh on November 13, 1831. His father's name was John Clerk Maxwell, who had inherited both the name and the estate of the Maxwells, whereas John's older brother, James's uncle, had inherited the Clerk estate. James's mother descended from a well-known Scottish family, the Clerks of Penicuick. John was a lawyer by profession, but acted as a society man and an enthusiastic, amateur scientist, who combined imagination and enthusiasm. Yet he was not really a genuine scientist or engineer, but he clearly reveled in the scientific world of Edinburgh. In the early part of the 19th century, Edinburgh was one of the leading scientific centers of Scotland and even the whole world. When John was still a young man he was something of an amateur inventor and he always maintained a strong interest in technical things. His son, James shared his father's interests in science and in technical things, and thus needed no encouragement to explore the various fruits of the industrial revolution. He was one of those boys who are always into things, trying to find out how they work, and what else they could be used for. His father gladly supported his son in these ventures. John planned to have his son, James, educated at the estate before sending him to the University. But when James's mother died, his father sent James to Edinburgh where he lived with his father's sister and received his education at the Edinburgh Academy.

James's early school years were relatively undistinguished. Yet in 1845 he shared almost all prizes and medals with his classmate and friend Lewis Campbell and in 1846 he had his first paper read at the Royal Society of Edinburgh. The paper was concerned with a new way of drawing ovals and was not truly outstanding. Maxwell was not sent to Edinburgh University until 1847, where he studied for three years before matriculating at Cambridge in 1850. He could have progressed in his study much more quickly than he actually did; he took his time and spent much time outside the study of his major, mathematics, and indulged in experiments in physics, as well as in poetry, the classics, and philosophy, in all of which he excelled. After graduating from Cambridge, Maxwell stayed on at Trinity first as a Bachelor Scholar and then as a Fellow. As a student he had already published a number of papers on mathematical

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[4]Hendry, p. 108–21 (*passim*). R.A.R. Tricker, *The Contributions of Faraday and Maxwell to Electric Science* (London: Pergamon Press, 1966), pp. 93–100; P.M. Harman, *The Natural Philosophy of James Clerk Maxwell* (Cambridge: Cambridge University Press, 1998), pp. 1–70; R.T. Glazebrook, pp. 9–72; L.A. Campbell and W. Garnett, *Life of James Clerk Maxwell* (London: MacMillan, 1882) and (New York, 1969) (Johnson Reprint).

subjects, but once he was free from his study for the tripos he turned his attention back to literature, philosophy and physics. His first attention went out to the theory of color vision and later to the theories of electricity and magnetism.

The subject of color vision had fascinated him since he was a young student in Edinburgh. The traditional theory which was then still taught in Edinburgh (Brewster), was built on the hypothesis of three different kinds of light (Red, Blue, and Yellow), distributed in varying degrees or proportions throughout the spectrum. A new theory based on three different receptors in the eyes had been put forward at the turn of the century by Thomas Young in the context of his wave theory of light. Yet this theory was neither proven nor taken seriously by many. Yet, following the success of Fresnel's wave theory of light, a number of scientists, including Maxwell, had independently revived the receptor theory in the 1840s. Maxwell in cooperation with Forges had been able to demonstrate that the primary colors were Red, Blue, and Green. They had also shown that the apparent primary nature of Yellow was a secondary absorption effect in pigments. Maxwell also began to test the receptor theory experimentally; he had constructed a color top with which to test the effect of different color combinations on different individuals. When he later returned to this subject, while still in Cambridge, he began to develop a set of personal color equations, showing, in particular, that color blindness results from a defect in one or more of the receptors, and to develop *a full set of exact color equations* for a typical, on average, fully-sighted individual. Today this theory is still held to be valid for color vision.

Maxwell continued his experiments on vision throughout the greater part of his life, but soon he turned the main focus of his research to *the science of electricity and magnetism.* This was another subject he had been interested in in Edinburgh. While studying there he, too, like Thomson some years earlier, had used Murphy's textbook which was built on the work of Poisson. But he, too, had soon become dissatisfied with the views of Poisson and Murphy. And he had there also become acquainted with the work of Faraday. Yet while he was in Cambridge, he had not yet immersed himself thoroughly in the subject. In February of 1854, after graduating, he wrote to Thomson about some problems he had run into and asked his advice on how to approach electric science *systematically*, what books to study and in what order, and particularly in what order he should study Thomson's own articles in *The Cambridge Journal.* We no longer have a copy of Thomson's reply, but we do know that it took the form of a long letter about electricity and that Maxwell took the advice of Thomson very seriously. Several years later he wrote in the *Preface* of his

own *Treatise on Electricity and Magnetism* that upon Thomson's advice he had started his research with a study of the work of Faraday.[5]

> Before I began the study of electricity I resolved to read no mathematics on the subject, till I had first read through Faraday's *Experimental Researches in Electricity*. I was aware that there was supposed to be a difference between Faraday's way of conceiving, and that of the mathematicians, so that neither he nor they were satisfied with each other's language. I had also the conviction that this discrepancy did not arise from either party being wrong. I was convinced of this by Sir William Thomson ...

From Maxwell's subsequent correspondence with Thomson we know that he combined the study of Faraday's work with that of Thomson's own papers. Only in 1855 did he take up the "heavy German writers" (Weber and Franz Ernst Neumann) and also the work of Poisson. But by that time he had already developed his own view on the subject, which was substantially the same as that which he later published in his own paper "*On Faraday's 'Lines of Force'*."[6]

In Maxwell's own view this paper was not meant to be an original contribution to the field, but rather a constructive review of the work done already:

> ...my object in doing so was, of course, to learn what had been done in electrical science, mathematical and experimental, and to try to comprehend the same in a rational manner by the aid of any notions I could screw into my head.[7]

As Maxwell saw things at that time, he found the topic very difficult and the existing investigations were so disconnected, that the establishment of a coherent survey of the existing knowledge and ideas seemed to constitute by itself already a significant contribution. At the beginning of the paper he

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[5]Maxwell, *A Treatise on Electricity and Magnetism*, 2 vols. (Oxford: Clarendon Press, 1873), Preface.

[6] *The Scientific Papers of James Clerk Maxwell*, ed. W.D. Niven, 2 vols., vol. 1, pp. 155–229.

[7] Letter of Maxwell to Thomson, 13 September, 1855, in J. Larmor, *Origins of J. Clerk Maxwell's Electric Ideas as Described in Familiar Letters to William Thomson* (Cambridge: Cambridge University Press, 1937), p. 17.

observed that electrical science as it stood at the time, was still a hodgepodge of unconnected or still incompletely connected areas, some of which lacked even the most basic empirical data, whereas others were the subject of masses of difficult mathematics. In his view any major development of the theory would have to incorporate connections between the different parts, and to do so in harmony with the existing laws. But to do this the first requirement was to make an effort to clarify and simplify the existing knowledge. And this was what he proposed to provide in the present paper and then, first of all, to excite appropriate *mathematical* ideas by using a "*method of physical analogy.*"[8] Before explaining, what *precisely* Maxwell meant by this expression, we must first consider the outcome of Maxwell's investigations as this is recorded in his letters to Thomson and in the published paper.

Maxwell felt that he had achieved *the mathematization of the work of Faraday.* This process had been started by Thomson. Yet where Thomson had concentrated on reconciling Faraday's results with the action-at-a-distance mathematics of traditional electrical theory, Maxwell started with Faraday's work, including his theoretical notions as well as his experimental results, to extract from them the appropriate key ideas, and then to seek a natural formulation for these ideas. The reason why Maxwell was attracted to Faraday's work to achieve this goal was the fact that Faraday's *Experimental Researches in Electricity* constituted a detailed survey of *all* that was known *experimentally* about electricity and magnetism and this survey could be taken as effectively theory-free.[9]

Yet once he began to know Faraday's work well, Maxwell realized that he had found much more there than just the empirical information he had been looking for, namely how to proceed on that basis. When he later in his *Treatise* recommended that every student should read Ampère's work as an example of "scientific style in the statement of discovery,"[10] he urged that one should also study Faraday for "the cultivation of a scientific spirit, by means of the action and reaction which would take place between the two newly discovered facts introduced to him by Faraday and the nascent ideas in his or her own mind."[11] And later he added to this that "if by anything I have here written, I may assist any student in understanding Faraday's modes of thought and expression, I shall regard it as the accomplishment of one of my principal aims—to communicate

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[8] Letter of Maxwell to Litchfield, 6 June, 1855, quoted in Campbell and Garnett, p. 156. Cf. *The Scientific Papers,* 1890, vol. 1, p. 15.

[9] Hendry, p. 124.

[10] Ibid.

[11] Maxwell, *A Treatise on Electricity and Magnetism,* 2 vols. (New York: Dover, 1954), vol. 1, p. 157.

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