INTRODUCTION

This third and final volume of James Clerk Maxwell's scientific letters and manuscript papers begins in 1874, with the opening of the Cavendish Laboratory, and concludes with his death on 5 November 1879. In this period Maxwell's main effort was concerned with the establishment and direction of the Cavendish Laboratory; to his duties as a Cambridge professor; to his work as author and reviewer, for the ninth edition of the *Encyclopaedia Britannica*, and as editor of *The Electrical Researches of Cavendish*; and to writing reports on papers submitted for publication in the Royal Society's *Philosophical Transactions*, a task to which he devoted much diligent labour. He served as a member of scientific committees appointed by the British Association for the Advancement of Science, taking a leading role in devising experiments to test the exactness of Ohm's law;(1) by force of circumstance his time and energy became directed towards public duties.(2)

(1) For Maxwell's work on testing the exactness of Ohm's law see the section on 'The Cavendish Laboratory' *infra*, and Numbers 561, 576, 577, 578, 590, 592, 600 and 619; on the Committee on the nomenclature of units see Numbers 517 note (9), 557 note (5) and 662 note (5); and for his work in determining the mechanical equivalent of heat see Number 597 note (3) and Plate VI.

(2) As a leading member of the scientific community Maxwell was drawn into public affairs. He was a co-signatory (with John Couch Adams, Thomas Andrews, James Prescott Joule, Balfour Stewart, William Thomson and others) of a letter to the Lords of the Committee of Council on Education urging the establishment of an observatory for astronomical physics: 'We, the undersigned, being workers in various departments of Science, are deeply interested in Astronomical Physics, and in the establishment by the British Government of an institution wherein this branch of research may be continuously promoted . . . Observatories for Astronomical Physics being already at work in various parts of Italy, and their immediate erection having being determined on at Berlin and at Paris . . . Your Lordships are aware that in the opinion of a considerable number of scientific men there is much reason to believe that a more or less intimate connection exists between the state of the sun's surface and the meteorology of the earth. A recent investigation made into the recurrence of famines in India appears to strengthen this hypothesis, in so far as it indicates an eleven-yearly period of such occurrences, which is nearly of the same duration as that of sun-spot frequency. The cyclones in the Indian Ocean appear likewise, as far as observation goes, to have a somewhat similar period. The establishment of the laws of this connection might ultimately open up the possibility of predicting the larger meteorological occurrences . . . For these reasons we beg to urge upon your Lordships that it is highly desirable that an Observatory for Astronomical Physics should be established by the State.' The reply from Lord Sandon (Vice-President of the Committee of the Council on Education), addressed to G. G. Stokes and Balfour Stewart, is dated 13 August 1877, suggesting that 'we believe that some advantages may be gained if a new class of observations can be made with the means already at

His lifelong friend and biographer Lewis Campbell recollected a conversation at Cambridge in 1877, the last time they met. On being shown the manuscript of *The Electrical Researches of Cavendish* Campbell enquired about Maxwell's own investigations: '"I have had to give up so many things", he answered, with a sad look, which till then I had never seen in his eyes.'(3) But it may be doubted that Maxwell envisaged that external demands would permanently thwart his ultimate commitment as a natural philosopher. In the year before his death he began to expand the scope of his work on statistical physics and the kinetic theory of gases, writing important papers on the theory of rarefied gases (Number 691) and on statistical mechanics (Number 698), giving his physics a new direction. Maxwell was alert and responsive to innovations in physical theory in the 1870s, to the work of Ludwig Boltzmann, Josiah Willard Gibbs, Hendrik Antoon Lorentz and J. D. van der Waals. His remark to Simon Newcomb in June 1879 (Number 744), that 'the dissipation, communication, and equilibrium of energy is the subject which at present best repays the labour of research' is suggestive; but the trajectory that his physics might have had after 1879 – developing thermodynamics, statistical physics and the theory of gases – can only be conjectured, cut off from fulfilment by his death from cancer at the age of forty-eight.

These new directions in Maxwell's science emerged from issues raised in the course of his work as reviewer, referee and author. His paper on statistical mechanics developed work by Boltzmann and H. W. Watson, following his review of Watson's *Treatise on the Kinetic Theory of Gases* in the journal *Nature* (Numbers 654 and 655). His paper on the theory of rarefied gases had its origin in the reports he wrote for the Royal Society on William Crookes' papers on the radiometer (Numbers 492, 559, 593, 681 and 719). His further development of the argument in treating gas–surface interactions (Number 742) was stimulated by reading a paper by Osborne Reynolds as a referee for the Royal Society (Number 736). Maxwell's discussion of molecular forces, the virial theorem and the equation of state (Numbers 522, 541, 542 and 543) was provoked by reviewing van der Waals' dissertation for *Nature*. His development of Gibbs' thermodynamic surface (Numbers 564 and 567) was made public in the text of the revised fourth edition of his *Theory of Heat*.

The pattern of Maxwell's correspondence changed during this period of his life. George Gabriel Stokes was now his Cambridge neighbour, and their correspondence in this period was largely concerned with the stream of reports which, as Secretary of the Royal Society, Stokes requested on papers submitted

command . . . by taking advantage of the facilities for carrying on work of this nature, which already exist at South Kensington' (from the printed copy of the correspondence in ULC Add. MSS 7656, SP1b).

(3) *Life of Maxwell*: 376. The meeting occurred in May 1877: see Number 646.

for publication in the *Philosophical Transactions*. Two of only four extant letters to William Thomson, in the past a major correspondent, were prompted by reports for the Royal Society. While the flow of letters and postcards exchanged with Peter Guthrie Tait was maintained, it diminished in regularity and intensity. The highlights of the correspondence with Tait include Maxwell's emphatic response to Tait's request for his opinion of Riemann's non-Euclidean geometry: 'The Riemannsche Idee is not mine' (Number 533). Their correspondence was sustained by Tait's requests for Maxwell's advice. Tait's revision of his *Sketch of Thermodynamics* generated Maxwell's pungent comment on Clausius' contributions to physics: on the theory of gases (Number 586), and on thermodynamics, where he rejects the proposed reduction of the second law of thermodynamics to a theorem in dynamics in trenchant terms – 'as if any pure dynamical statement would submit to such an indignity' (Number 623). Other letters bear on the (anonymous) publication of *The Unseen Universe*, Tait's contribution to current debates on materialism (Numbers 547, 554 and 560); and there is allusion to the topology of knots, the subject of Tait's interest in this period (Numbers 639, 640, 651 and 658). Maxwell's correspondence shows him forging relationships with the younger generation of physicists whose careers he fostered and whose outlook was shaped by his own style of physical theorising: the emergent Maxwellian physics. His attention turned to direct research at the Cavendish Laboratory, shaping the work of George Chrystal and William Garnett, and of Arthur Schuster (Number 610), who joined the Laboratory from outside the University.

While Maxwell's scientific life and public career is profusely documented, little information can be gleaned about his private affairs. Contemporary recollections are sparse and generally bland and unrevealing, observing the public proprieties. But Henry Rowland, whose work he encouraged (Numbers 515, 520, 592 and 739) and who visited Glenlair in July 1875 (Number 568), gave an informed and perceptive outsider's impression. After his visit Rowland wrote to Daniel C. Gilman, President of The Johns Hopkins University, reporting on his encounters with British physicists: 'As for the professors I have yet met, they are all men like the rest of us! After seeing Maxwell I felt somewhat discouraged for here I met with a mind whose superiority was almost oppressive.'[(4)]

Cambridge professor

Appointed to the new professorship of experimental physics at Cambridge in March 1871 Maxwell delivered his inaugural lecture on 25 October 1871, and commenced regular lecturing duties. The professorship had been established to

(4) H. A. Rowland to Daniel C. Gilman, 14 August 1875 (Gilman Papers, Milton S. Eisenhower Library, The Johns Hopkins University, Baltimore).

provide 'public instruction in Heat, Electricity and Magnetism', it having been agreed to add these subjects to the examination for the Mathematical Tripos in 1873.[5] Stokes had informed Maxwell in February 1871 that his lectures would be 'subject to the approval of the board of Mathematical Studies'; it was anticipated that candidates for the Mathematical Tripos who opted for physical subjects, as well as candidates for the Natural Sciences Tripos, would attend.[6] Maxwell lectured on the prescribed physical subjects, fulfilling the requirement that his professorship meet the scope of the Mathematical Tripos when the new regulations came into force in 1873. He was appointed to the new post of Additional Examiner for the 1873 Tripos, having special concern with problems in physical subjects; and as President of the Board of Mathematical Studies he invited Sir William Thomson to serve as Additional Examiner for 1874,[7] Peter Guthrie Tait for 1875 (Numbers 502, 507, 513, 523, 538 and 540), and Lord Rayleigh for 1876 (Numbers 551 and 553).

In 1873–4 Maxwell announced lectures on 'Heat and Elasticity' in Michaelmas term 1873, on 'Electricity and Magnetism' in Lent term 1874, and on 'Electromagnetism' in Easter term 1874,[8] continuing the pattern of his lectures in previous years. But the direction and content of the lectures changed between 1871 and 1879. George Howard Darwin's notes on Maxwell's lectures delivered in Michaelmas term 1873 and Lent term 1874 show that at this time he lectured on mathematical physics at an advanced level of mathematical sophistication.[9] The lectures were clearly directed at prospective high wranglers rather than intended for candidates for the Natural Sciences Tripos, for which Maxwell served as an examiner in 1873 and 1874 (Number 540). In 1876 the examination for the Natural Sciences Tripos was divided into elementary and advanced parts, with physics examined as a separate subject.[10] As an examiner in December 1873 Maxwell had reported to the University that several candidates 'sent up answers which showed that Experimental Physics, treated without the higher mathematics,

(5) For the establishment of the professorship see *Cambridge University Reporter* (16 November 1870): 93–7; and see J. Clerk Maxwell, *Introductory Lecture on Experimental Physics* (London/Cambridge, 1871) (= *Scientific Papers*, **2**: 241–55). The MS of the lecture is preserved in ULC Add. MSS 7655, V, h/7.

(6) G. G. Stokes to Maxwell, 18 February 1871 (ULC Add. MSS 7655, II/41), printed in Volume II: 612 note (4).

(7) See Volume II: 839.

(8) *Cambridge University Reporter* (14 October 1873): 23; *ibid.* (14 January 1874): 185; *ibid.* (14 April 1874): 315.

(9) G. H. Darwin's notes in ULC, DAR.210.22; see Volume II: 36, 940–1 note (5).

(10) See *The Cambridge University Calender for the Year 1876* (Cambridge, 1876): 37–9; and see David B. Wilson, 'Experimentalists among the mathematicians: physics in the Cambridge Natural Sciences Tripos, 1851–1900', *Historical Studies in the Physical Sciences*, **12** (1982): 325–71, esp. 343–6.

may be learned in a sound & scientific manner';[11] and he transformed the scope of his lectures to address candidates for the advanced part of the Tripos. From 1876–7, lecturing on 'Heat and the constitution of bodies', on 'Electricity' and on 'Electromagnetism', his lectures were complemented by William Garnett's 'Elementary lectures on physics' (Number 635), intended for candidates for the elementary part of the Natural Sciences Tripos and for other students requiring instruction in physics.[12] The notes taken by Ambrose Fleming recording Maxwell's lectures in 1878–9, the last session in which he lectured, show that he then expounded a range of physical topics without appeal to advanced mathematics;[13] but with few candidates for the Natural Sciences Tripos, attendance was low (Number 740).[14]

Professorial lectures were not however the significant medium for instruction in Cambridge in the 1870s. Coaches still had primary responsibility for preparing candidates for the Mathematical Tripos. E. J. Routh, who had graduated senior wrangler above Maxwell in 1854, was the leading coach; he introduced electricity and magnetism into his teaching, incorporating many of the mathematical methods explicated in Maxwell's *Treatise on Electricity and Magnetism*, while making no reference to Maxwell's field theory. In 1876 W. D. Niven established an intercollegiate class at Trinity College, offering a systematic exposition of the *Treatise*; in contrast to Routh, Niven drew attention to Maxwell's field theory.[15] The teaching

(11) The text is printed in Volume II: 964.

(12) Lectures on 'Heat and the constitution of bodies' by Maxwell and 'Elementary lectures on physics' (subject unspecified) by William Garnett (Michaelmas term 1876); 'Electricity' by Maxwell and 'Heat and light' by Garnett (Lent term 1877); and 'Electromagnetism' by Maxwell and 'Electricity and magnetism' by Garnett (Easter term 1877), were announced in the *Cambridge University Reporter* (24 October 1876): 59; *ibid.* (16 January 1877): 195–6; *ibid.* (20 March 1877): 310; and *ibid.* (10 April 1877): 366.

(13) Ambrose Fleming's notes on Maxwell's lectures in the session 1878–9 are recorded in two notebooks: 'Notes on Thermodynamics/ Prof. Maxwell's Lectures/and other abstracts, taken during the October term 1878' (ULC Add. MSS 8082); and his notes on 'Prof. Clerk-Maxwell's Lectures on *Electricity* /taken during the Session 1878–1879/Electrostatics January 1879/Electromagnetism April 1879' (ULC Add. MSS 8083). Fleming's notes on '*Electricity*' provided (ff. 29–30) the basis of §282*b* in the *Treatise* (2nd edn), **1**: 374 (see Number 532 note (11)); and notes on the 'Distribution of Currents in Network of Conductors' (ff. 84–6), to which he appended 'Maxwells Last Lecture . . . ', form the basis of the addendum to §755 in the *Treatise* (2nd edn), **2**: 365. Maxwell's lectures on 'Heat and the constitution of bodies' (Michaelmas term 1878), 'Electricity' (Lent term 1879) and 'Electromagnetism' (Easter term 1879) were announced in the *Cambridge University Reporter* (15 October 1878): 37; *ibid.* (24 January 1879): 350; and *ibid.* (22 April 1879): 530.

(14) Ambrose Fleming, 'Some memories . . . ', in *James Clerk Maxwell: A Commemoration Volume, 1831–1931* (Cambridge, 1931): 116–24.

(15) Andrew Warwick, *Masters of Theory: A Pedagogical History of Mathematical Physics at Cambridge, 1760–1930* (Chicago/London, forthcoming): chapter 6.

of Routh and Niven helped shape the interests of the new generation of wranglers. George Chrystal, second wrangler in 1875, who had attended Maxwell's lectures in Michaelmas term 1873, was one of Routh's pupils; on reading the *Treatise* in July 1874, and encountering difficulties, he wrote to Maxwell seeking clarification (Number 518). Joseph Larmor and J. J. Thomson, senior and second wranglers in 1880, attended Niven's lectures. The transformation of wranglers into physicists in Cambridge in the 1870s, and the emergent interest in Maxwell's electromagnetic theory as the focus of research, was clearly shaped by Maxwell's presence and stature and by the establishment of the Cavendish Laboratory; but Maxwell's own lectures and the instruction in experimental physics offered within the Laboratory played a relatively minor role in effecting this development.

Maxwell served as an examiner for both of the prizes offered by Cambridge mathematics: the high wranglers in the Mathematical Tripos competed in the annual examination for Smith's Prizes; while the Adams Prize elicited original research. The limited incursion of Maxwellian physics – even of the mathematical theories of heat, electricity and magnetism – within Cambridge mathematics in the 1870s is apparent in the range of questions which Maxwell set in his examination for the Smith's Prize in January 1879 (Number 727). His questions ranged over the traditional core of Cambridge 'mixed mathematics': geometry, geometrical optics, dynamics and hydrodynamics. Of the fifteen questions set only two were directly concerned with problems in the physics of electricity, but not with Maxwell's field theory, and these questions attracted little response from the candidates.(16) In February 1875 Maxwell was appointed an examiner for the Adams Prize for 1877, and he drafted questions on the reduction of the second law of thermodynamics to dynamics, on anomalous dispersion and on Boltzmann's theorem of the equilibrium of energy (Number 549), problems arising from his own interests in physics. These questions did not apparently find favour with his co-examiners, James Challis and G. G. Stokes. The subject agreed for the prize was on dynamical stability, a topic – closer to the core of Cambridge mathematics – which however bore on Maxwell's own interest in stability criteria for dynamical systems; he had himself won the Adams Prize for 1857 for his essay on the stability of the motion of Saturn's rings.

(16) Maxwell endorsed the printed text of his personal copy of the paper he set for the Smith's Prize examination with the names of candidates attempting the questions (see Number 727). The 1879 Smith's Prize examination, set by Maxwell, Arthur Cayley and Isaac Todhunter (see *The Cambridge University Calendar for the Year 1879* (Cambridge, 1879): 606–12), drew criticism from G. B. Airy on the grounds of an excessive focus on pure mathematics, making specific complaint of a question in Cayley's paper; see June Barrow-Green, '"A corrective to the spirit of too exclusively pure mathematics": Robert Smith (1689–1768) and his prizes at Cambridge University', *Annals of Science*, **56** (1999): 271–316, esp. 298–9.

Maxwell played his part in the meetings of the Cambridge Philosophical Society, the forum for scientific life in the University. He served as President in 1876–7 (Number 641) and presented several papers to the meetings, the most important being his paper on statistical mechanics read in May 1878 (Number 698). He served as an examiner for Trinity College fellowships, reading dissertations submitted by the candidates (Numbers 573, 623, 645 and 669).(17) He made another important contribution to the life of the University in delivering his Rede Lecture on 'The telephone' in May 1878 (Number 701). There was great public interest in Alexander Graham Bell's recent invention and Maxwell readily concurred with the Vice-Chancellor's choice of subject (Number 697). Demonstrating the technique of telephony, he spiced the science with quotations from Milton and Tennyson, striving to engage his audience by placing the topic within a context of literary culture. Drawing upon accounts of the telephone and its history he ranged over a cluster of problems in the history of acoustic inventions, the attempts to imitate vocal sounds by means of speaking machines. He had invited lectures on acoustics in the Cavendish Laboratory (Numbers 646, 648 and 694), and his Rede Lecture reveals his own breadth of knowledge of the subject. He participated in the wider intellectual life of the University, joining a group of older scholars – some of whom had been Apostles in the 1850s – in the Eranus Club, reading two papers to the group (Numbers 625 and 685).

The Cavendish Laboratory

Immediately upon his election to the professorship of experimental physics at Cambridge in March 1871 Maxwell began to draw up plans for the design of the Laboratory and the acquisition of apparatus. In prompting the University to establish the professorship the seventh Duke of Devonshire, as Chancellor, had offered 'to provide the funds required for the building and apparatus'.(18) In June 1873 Maxwell drew up a proposed 'list of fixtures & principal instruments in the different rooms' of the 'Cavendish Laboratory',(19) as the laboratory was

(17) In a letter to Maxwell dated 30 August [1878] (ULC Add. MSS 7655/211) Thomas Dale, Tutor and Lecturer in Mathematics at Trinity College, mentioned nine candidates, noting that 'Poynting, McCann, Sunderland and Main [are in] for their 3rd & last time'. J. H. Poynting (third wrangler 1876) was elected to a fellowship at Trinity in 1878, returning to Cambridge to pursue research at the Cavendish Laboratory on the measurement of the mean density of the earth; see Number 764X note (3). Referring to a Trinity dissertation, which he enclosed with a letter to Maxwell dated 30 July [ ] (ULC Add. MSS 7655, II/209), Arthur Cayley remarked on 'an Essay by Knight, which I shall be glad to have again . . . it is really a very creditable production'.

(18) The seventh Duke of Devonshire to the Vice-Chancellor, John Power, 10 October 1870 (ULC, V.C. Corr. I.2), printed in the *Cambridge University Reporter* (19 October 1870): 13.

(19) Volume II: 856–75.

now called, from the family name of the dukes of Devonshire. Few of these instruments had been acquired by the time the Laboratory opened (Number 506). On presenting the Laboratory to the University the Duke repeated his intention to present the principal instruments and apparatus (Numbers 516 and 558), an undertaking that was munificently fulfilled. Shortly after the formal inauguration on 16 June 1874 Maxwell gave the Vice-Chancellor an account of his acquisition of the 'principal instruments' (Number 516); and in July 1877 he calculated that the Duke had given £14,763 to the Laboratory, including £10,939 expended on the building and £2,257 on instruments.[20] Maxwell contributed to the purchase of equipment (Numbers 516, 519 and 704), and donated the apparatus he had used in his own experiments (Numbers 496, 500, 508 and 558). In April 1875, in the first of his annual reports to the University (Numbers 558, 601, 644, 693 and 740), he recorded the purchase of many of the instruments he had listed in June 1873.

In 1863–4 Maxwell had collaborated in experiments at King's College London in determining the British Association standard unit of resistance, the 'ohm'. It had become apparent that these experiments were insufficiently accurate, and that there was significant error in the resistance standards issued in 1865. Following his election to the professorship Maxwell declared that he intended to re-determine the 'ohm', though he disclaimed intention to issue standards, to establish a 'manufactory of "ohms"' (Number 548). While this project was not carried through during his lifetime, it became a major objective in his direction of the Cavendish Laboratory, continued by his successor, Lord Rayleigh. The acquisition of the spinning coil and other apparatus used in the original experiments was one of his first acts at the opening of the Laboratory (Numbers 495, 498, 517 and 534).

The Laboratory was open to 'any Member of the University who may desire to acquire a knowledge of experimental methods, or to take part in physical researches'.[21] But research and laboratory instruction, guided by Maxwell and the Demonstrator, William Garnett, available to both undergraduates and graduates, was constrained by the limited institutional base at Cambridge for education and experimental work in physics. Recruitment into the Laboratory was drawn largely from graduates of the Mathematical Tripos, whose scientific knowledge was limited. When the first students were instructed in taking galvanometer readings, Maxwell fostered their induction into the new laboratory culture by translating the observations of the experimenters into mathematical language (Numbers 515 and 534). Seeking to turn wranglers into physicists, to

(20) See Number 650 note (10).
(21) *Cambridge University Reporter* (24 October 1876): 59.

wrench their minds from symbols to concrete apparatus, he devised a model to illustrate the mutual induction between coupled circuits (Number 630).

Maxwell's engagement with experiments and instruments led him to examine the principles determining the design of the apparatus used in physics. He served as a member of the organising committee of the Special Loan Collection of Scientific Apparatus held at the South Kensington Museum in 1876 (Number 602), writing the general introduction in the exhibition's *Handbook*.(22) Here he discussed the design of apparatus and instruments, seeking to establish principles for the construction and use of apparatus. He set out a common classification of the functions of instruments, a taxonomy based on energy physics, which he applied to the operations of mechanical instruments, to pressure instruments and to instruments used in the sciences of heat, electricity, optics and acoustics. The exhibition had practical import in providing direct evidence of contemporary achievement in instrument design and manufacture; and he ordered several instruments for the Cavendish Laboratory from German instrument makers (Numbers 633, 636, 644 and 664).

Struggling to refine apparatus and to acquire instruments Maxwell also wrestled with the problem of bridging the gulf between the instrument maker and the experimenter, to ensure that workshop practice was directed to the needs of the Laboratory (Number 644).(23) The technician Robert Fulcher was employed in the Laboratory from 1877, providing expertise in the construction of precision apparatus (Number 693). But the researchers were few in number and were neophytes, and Maxwell advised rather than directed their efforts. He did however encourage research to provide experimental validation of his electromagnetic theory of light, and here he devised the experiments and superintended the work. In 1874–6 he directed J. E. H. Gordon's measurement of 'Verdet's constant', bearing on his interpretation of the Faraday magneto-optic effect (Numbers 546, 561 and 603). In 1877–8 he directed Gordon's measurement of dielectric constants, work undertaken to test the relation between the refractive index and the dielectric constant of transparent dielectrics posited by the electromagnetic theory of light (Number 714). Precision experiments, the exact comparison of electric units and the measurement of coefficients, seemed at the time to be the

(22) J. Clerk Maxwell, 'General considerations concerning scientific apparatus', in *South Kensington Museum. Handbook to the Special Loan Collection of Scientific Apparatus 1876* (London, 1876): 1–21; and see his note on 'Instruments connected with fluids', *Handbook*: 89–92 (= *Scientific Papers*, **2**: 505–22, 523–7).

(23) On the relation between workshop and research at the Cavendish Laboratory see Simon Schaffer, 'Accurate measurement is an English Science', in *The Values of Precision*, ed. M. Norton Wise (Princeton, 1995): 135–72.

most plausible basis for providing experimental demonstration of the electromagnetic theory of light. But in 1874 W. M. Hicks, one of the first students to work in the Laboratory (Number 558), set up an experiment to measure the velocity of propagation of electricity between coils, apparently seeking to effect electromagnetic waves.(24)

The rigorous testing of Ohm's law was the first major experimental project carried out under Maxwell's direction at the Cavendish Laboratory. At the meeting of the British Association for the Advancement of Science at Belfast in August 1874, which Maxwell attended, Arthur Schuster had described experiments which led him to suspect a deviation from Ohm's law.(25) A committee was established, with Maxwell and Schuster as members, to undertake experimental tests to establish the exactness of the law. Maxwell assumed responsibility for the investigation, devising the experimental arrangements; and on joining the Laboratory George Chrystal carried through the work (Number 561). Maxwell gave an account of the course of the experiments in letters to H. A. Rowland and Schuster, written between November 1875 and May 1876. His first method of testing involved the measurement and comparison of the resistances of a system of five coils; these experiments, which suggested a very small apparent deviation from Ohm's law,(26) were completed by late 1875 (Numbers 576 and 577). The second and more exacting method involved the comparison of strong and weak currents passed alternately through the wires many times in a second (Number 578); and in the final experimental arrangement the alternation was managed by a pair of electric tuning-forks (Numbers 590 and 592). Writing to Schuster in May 1876, Maxwell was now able finally to conclude that these very searching tests confirmed the accuracy of Ohm's law (Number 600). He summarised the work in a report to the meeting of the British Association at Glasgow in September 1876 (Number 619), placing its presentation in the charge of Chrystal and Schuster (Numbers 618, 620 and 621).

Maxwell had emphasised measurement and the establishment of 'a numerical estimate of some magnitude' as the true aim of 'Experiments of Research' in his inaugural lecture at Cambridge in October 1871,(27) but the realisation of this style of experimentation in the Cavendish Laboratory required precision instruments and trained personnel to bring the work to fruition. Chrystal's success in carrying through the testing of Ohm's law, performing the difficult

(24) Arthur Schuster, 'The Clerk-Maxwell period', in *A History of the Cavendish Laboratory 1871–1910* (London, 1910): 14–39, on 19; and see Thomas K. Simpson, 'Maxwell and the direct experimental test of his electromagnetic theory', *Isis*, **57** (1966): 411–32, on 425–6.

(25) See Number 576 note (5).

(26) See Number 577 esp. note (7) and Number 619.

(27) Maxwell, *Introductory Lecture*: 7–8 (= *Scientific Papers*, **2**: 242–3); and see Number 512.