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Other chapters in this book cover a wide range of Maxwell's career and interests.

Maxwell at King's College, London

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LONDON AND MAXWELL'S APPOINTMENT

London was a place of completely different character to Aberdeen, where Maxwell had spent the past four academic years. London was the chief town of the British Empire, "*the emporium of England, the centre of its great monetary transactions, the home of its science, literature, and art, and the yearly resort of its aristocratic and landed proprietor classes*" according to one roughly contemporary description[1]. It is debatable whether it was the home of British science. It was the home of the Royal Society of London (founded 1660), a meeting place for a wide variety of scientists of distinction and a publishing house but not an institution with significant scientific facilities; it was the home of the Royal Institution (founded 1799) whose successive Resident Professors had a laboratory and made very good use of it, though the main mission of the Institution was promoting science. Gresham College had existed since the mid 16th century with a lecturing professoriate. The Royal Observatory at Greenwich had maintained its reputation as one of the world's premier observatories since its foundation in 1675 but what almost beggars belief is that as late as the beginning of the nineteenth century London, the wealthiest and most populous city in the world, had no universities at all. By any comparison with the great academic cities of Europe whose Universities went back more than 500 years, London was not an academic city[2]. Did this make any difference? It's a curious fact that in spite of a population of some 2.8 million in Maxwell's time (14% of the total population of England and over half a million more than the city of Paris in 2010), very few 19th century natural philosophers of note were born in London. The inference from these statistics is that in the spectrum of London's achievements, science was not near the top. In complete contrast to Aberdeen, however, it *was* a place one happened to pass through on many a journey. It was a place that embodied change in general and exchange of ideas in particular. Maxwell could hardly have moved to a better city to maintain himself on the stage where science was exhibited.

By the time Maxwell arrived in 1860, London had two university colleges, founded within a few years of each other. In brief, the University of London was founded on paper in 1826 and University College opened for business in new buildings in 1828. The significant motivation for its founding was not the perceived want of a University in the great capital city but the fact that the other English Universities of Oxford and Cambridge were so closely tied to the United Church of England and Ireland (as it was then) that non-conformists and others of different faiths were at the time prohibited from graduating or becoming Fellows[3]. University College was to be explicitly non-denominational. Indeed theology was excluded from a portfolio that was otherwise as wide as any long-established university.

King's College, London was founded just a year later (1829) with a similar plan of instruction but with a remit to include "*the doctrines and duties of Christianity, as the same are inculcated by the United Church of England and Ireland*". The religious link is echoed in the College motto '*Sancte et Sapienter*' and theology was included in the subjects on offer. King's took in its first students in 1831, initially in premises in a wing of Somerset House before building their college on an adjacent site. Notwithstanding the establishment slant that had motivated its founders, dissenters were allowed to attend classes from the beginning. Both institutions, as oases in the desert, had no difficulty attracting students in the early decades. In 1836, the University of London was redefined as simply an examining body that would oversee the academic output of the two separate Colleges; a merger that at the same time maintained much of their autonomy. It was a model that Aberdeen could have followed with profit but the Aberdeen Royal Commissioners chose not to.

For historians, the Aberdeen Commissioners did leave one important legacy. They opened up the working of the two Universities there to the scrutiny of the public and posterity. No such transparency exists for King's College, London. It was a new university, scarcely 30 years old when Maxwell arrived, still finding its academic and financial feet, still making major changes to its portfolio of professors and courses, still building its reputation and place in the capital[4, 5]. Moreover, it was a 'new university' in its outlook too, emphasising explicitly its rôle in providing training for the rising professional classes. The want of and need for science-based education in England had been highlighted by Lyon Playfair in an impassioned discourse[6] to the Society of Arts following the success of the Great Exhibition in 1851. This exhibition had made it clear that to sustain a competitive place in the world of invention and manufacture required a scientific and technical base that the traditional education in England was providing inadequately. King's College was at least moving in the right direction in the view of the modernisers, though Lyon Playfair would have had it providing post-graduate education too.

Just as Maxwell brought with him diverse interests from Cambridge to Aberdeen, so he brought his Aberdeen interests to London for continuation. His King's College years are notably characterised by the gelling of his thoughts on the mathematical representation of Faraday's electric and magnetic fields. This led to what is now commonly seen as his greatest achievement, the full unification of electric and magnetic phenomena, with his prediction of electromagnetic waves. His contemporaries, though, regarded his work on molecular science as more fundamental and this, too, developed as he was leaving King's College.

Fig. 1 *The Institute of Physics Blue Plaque at King's College.*

Before arriving in London, Maxwell had followed up his 1859 BA papers with further presentations on colour vision and the dynamics of gases at the Oxford BA meeting in June 1860 (the still famous meeting where Thomas Huxley met Bishop Wilberforce in an influential exchange on Darwin's theory of evolution). He was appointed to King's College as Professor of Natural Philosophy in July 1860, some two months after losing out in Edinburgh. His duties were "*To instruct* **all** *the Students of the Department of Applied Sciences in the principal Mechanical Sciences, including Statics, Dynamics, Hydrostatics, Pneumatics, Hydraulics, together with Optics and Astronomy*"[7]. He was required to be in College three mornings a week from 10 am to 1 pm and to teach an evening class for an hour a week. The salary was 5 guineas (£5.5.0) per annum for each matriculated student, £0.18.0 for each evening class student and £2.7.3 for each Occasional Student (mentioned later) per term. Though we don't know exact numbers of students in the last two categories, this works out at around £450 per annum, a moderate step up from his Aberdeen income. Out of the five named candidates[8] for the post, Maxwell was appointed unanimously.

Fig. 2 *Palace Gardens Terrace, London, in spring 2011. Maxwell's residence at No. 16 (formerly no. 8 in his day) is in the centre of the picture. A London County Council blue plaque shown in Fig. 2a is above the balcony but hidden by the foliage in this picture. Photograph by Anne Ross Muir.*

After a troubled September when Maxwell caught smallpox at Glenlair and was nursed through his illness by Katherine, the Maxwells took up residence in their leased home at 8 Palace Gardens Terrace, Kensington (renamed as number 16 after the Maxwells left) . The Kensington district alone had a population in 1861 twice that of Aberdeen. The address was within easy access of Kensington Gardens and Hyde Park but a good hour's walk from King's College, when Maxwell chose to walk. As recorded in the 1861 census, they had a cook and a Scottish housemaid. It would have made sense to employ Glenlair staff.

Fig. 2a *London County Council blue plaque on Maxwell's house at 16 Palace Gardens Terrace.*

On a personal level, a London residence made it more likely he would see friends passing through and gave him ready access to activities at the Royal Institution and, soon, the Royal Society of London. He was awarded the Rumford Medal of the Royal Society in November 1860 for his work on colour vision and he was elected Fellow of the Royal Society in May 1861. His King's College years are frequently described as his most productive but the fact is he received all his major honours (Smith's Prize, Adams' Prize, Rumford Medal and election to the Royal Societies of Edinburgh and London) largely for the work he carried out before he came to London.

COLOUR VISION AND COLOUR PHOTOGRAPHY

One very important application came out of Maxwell's work on colour perception, one that he had foreseen as early as 1855. He realised that to achieve almost full colour reproduction one only needed to combine together views taken in three primary colours. This could be done in principle by photographing the scene on a black and white plate through a red filter, to record the red component, and likewise making two separate photographs of the same scene through green and blue (or violet as Maxwell mentioned) filters. Positives are made from the plates (or they are made directly by suitable processing). Projecting the three positives simultaneously into a composite image on a screen using three separate projectors, each including the same filter the positive was taken through, would reconstruct the original coloured scene.

The implementation doesn't sound too difficult but the fact is that it required a photographer of skill, perseverance and, as will be seen, with some luck to pull it off. No-one had reported attempting it since Maxwell first mentioned the idea in a Royal Society of Edinburgh paper of 1855. Maxwell is correctly credited with being the father of colour photography but his efforts did not herald the on-set of colour photography. For example, Charles Fabre's eight-volume encyclopaedic treatise of photography mainly issued over the 1890s[9] has no references to Maxwell's work and virtually nothing on colour photography. Maxwell's 'proof of concept' that he was about to demonstrate in 1861 remained just that until almost into the twentieth century, an academic demonstration.

The exceptional photographer Maxwell needed was Thomas Sutton. He had been a Cambridge wrangler and established a successful photographic business based in Jersey that claimed the patronage of Prince Albert[10]. In 1859 Sutton had come to the British Association meeting in Aberdeen to present a paper on his newly invented, distortion-free triplet photographic lens (a pre-cursor to the highly successful Cooke triplet of some 34 years later). Maxwell may have spoken with him but in one of life's coincidences, King's College, London had run photographic instruction since 1857 and Thomas Sutton was appointed the College photographer in October 1860 upon the resignation of the incumbent. Maxwell and Sutton must have spent many hours in the college sunshine and in the college basement getting the technique to work. Maxwell had a commission to give a Friday evening discourse to the Royal Institution on the theory of three primary colours in May of 1861. The subject they chose to photograph was a suitable multi-coloured ribbon, probably one that belonged to Katherine. It is often described as a 'tartan' ribbon, though tartans usually have only two dominant colours. Since their results were projected onto a screen at the Royal Institution, only the audience knew exactly what the image looked like. We do know, though, that the colour reproduction wasn't of the quality we now expect and Maxwell himself in the published note of the talk says "*by finding photographic materials more sensitive to the less refrangible rays* [i.e. green and red in particular], *the representation of the colours of objects might be greatly improved*"[11].

Coloured versions of the projected image of the ribbon can be found on the web and elsewhere. They come from reproductions made using a copy of the original positive plates by Kodak to mark the centenary of the event[12]. Kodak also tried to reproduce Sutton's technique. They realised that the original plates were not sensitive to green and red and hence Maxwell's demonstration should not have worked at all. Mid-nineteenth century photographers were pioneering the whole technique of photography and did not seem to be aware of the very limited spectral sensitivity of the wet collodion plates then in use, sensitivity that was restricted to the blue and violet end of the spectrum and continued into the ultraviolet. The plates better represented the spectral sensitivity of a bee's eye than a human's, though that was not known at the time. What Maxwell and Sutton actually achieved was the world's first false-colour image, the recorded ultraviolet image being shown in red. False-colour imaging is now the most common imaging technique used in remote sensing from space, where X-ray, ultra-violet and infra-red images can be recorded by instruments sensitive well beyond the limits of human vision. Maxwell was certainly correct in his reasoning of how a full colour image could be made and in suggesting what was wrong with the demonstration.

Sutton left the employ of King's College after only a year. At the Manchester BA meeting in 1861 he described his unusual panoramic lens (an extreme development of his triplet) and at the BA meeting in Cambridge in 1862 he described a rapid-drying collodion process. The panoramic lens attracted significant attention in the 1862 exhibition mentioned later and is illustrated and described at length in the official record of the exhibition cited later. His name is remembered by some photographers as the patentee in 1861 of the first single-lens reflex camera though, like the colour photograph, the idea took decades to catch on. Sutton deserves more credit than he has been given for enabling Maxwell's ideas to be realised, albeit imperfectly.

Photographic emulsions that were sensitive across the range of colours that we see did not appear until the second half of the 1870s, which was the earliest that a genuine demonstration of 3-colour photography could have been made. The first partially successful technique was developed by John Joly in Dublin in the mid 1890s, using a 3-colour additive process with colour filters that mimicked on a sub-millimetre scale Maxwell's method. The colours were approximate and muted; the practical details tricky. In the event, Maxwell's 3-colour additive technique was finally incorporated into commercial film in products such as Autochrome and Dufaycolor early in the 20th century and is of course the basic colour reproduction mechanism used in colour television, mobile phones and today's 3-colour CCD-based imaging systems.

MAXWELL'S KING'S COLLEGE TEACHING

Maxwell arrived at King's College with experience and courses in hand for teaching students new to Natural Philosophy, for teaching advanced students and for evening classes. King's College could hardly have expected any better experience in their appointee, for he would have to undertake similar courses there. The workload was lighter than at Aberdeen but still significant and only someone who valued the whole teaching experience would take it on. One story from his Aberdeen years that was related by Campbell and Garnett is this: *The professors had unlimited access to the library, and were in the habit of sometimes taking out a volume for the use of a friend. The students were only allowed two volumes at a time. Maxwell took out books for his students, and when checked for this by his colleagues explained that the students were his friends*[13]. When you see students as friends, you value the opportunity to teach. Maxwell had done the hard work in Aberdeen of thinking about his subjects but the context at King's was different and his courses needed to be tailored to the new circumstances, circumstances that were in detail different from those in Aberdeen.

King's College was divided into four 'Departments', better considered as 'Faculties' in 20th century University language. They were 'Theology', 'General Literature and Science' (which included botany, zoology, Wheatstone's chair of Experimental Philosophy and also a wide range of foreign languages), 'Applied Sciences' and 'Medicine', the largest department in terms of student numbers. Maxwell was in the Applied Sciences Department that hosted the 'Engineering Section' and the 'Military Section' as far as student programmes were concerned. Most students in this Department enrolled in the Engineering Section. Its objects were '*to provide a system of general education, practical in its nature, for the large class of young men who, in after life, are likely to be engage in commercial and agricultural pursuits, or in professional employments, such as Civil and Military Engineering, Surveying, Architecture, and the higher branches of Manufacturing Art*'[14]. Thirteen subjects were taught in the Engineering Section of which Maxwell's was 'Natural Philosophy and Astronomy'. The minimum entrance age in this section was 16. For students in the Military section, it was just 15.

It is interesting to compare Maxwell's professorial colleagues in Applied Sciences when he arrived with the Marischal College staff discussed in the previous chapter. They were Prof. Rev. Thomas Grainger Hall in *Mathematics*, in post since 1830, Dean of the Engineering section and author of several textbooks on calculus, descriptive geometry and trigonometry, with Rev. T. A. Cock as Lecturer in Mathematics and Rev. Walter Howse as Assistant Lecturer in Mathematics; Prof. William Hosking *Civil Engineering and Architecture*, railway engineer, bridge designer and architect, appointed in 1840 but died in 1861[15], with A. Moseley as Lecturer in Civil Engineering; Prof. Charles Percy Bysshe Shelley, *Manufacturing Art and Machinery*, later author of textbooks on applications of heat, workshop appliances and co-author with T. M. Goodeve of a treatise on Joseph Whitworth's measuring machines; Henry James Castle, Lecturer in *Land Surveying and Levelling*, present since 1839 whose book with F. W. Simms on mathematical drawing instruments, the theodolite and levelling first published in 1837 is, amazingly enough, still in print; Professor Thomas Bradley, *Geometrical Drawing* (author of a detailed work on Practical Geometry, Linear Perspective and Projection) with Fredrick Alfred Bradley as Lecturer; Professor William Allen Miller FRS *Chemistry* (medical doctor, author of a popular textbook on the elements of chemistry, notable for his wide-ranging scientific interests, particularly in spectroscopy) with K. A. Haddow as demonstrator; Professor Charles Loudon Bloxam *Practical Chemistry* (whose own long-running textbook on inorganic and organic chemistry first published in 1867 would complement Miller's elements of chemistry[16]); Professor James Tennant FGS *Mineralogy* and *Geology*, a highly respected mineralogist and geological collector who had been with King's since the inauguration of its Engineering course in 1838. Tennant's collection of over 5000 minerals is now with Royal Holloway College, University of London.

As at Aberdeen they were competent University men. They covered a wider range of technical subjects than Maxwell's Aberdeen counterparts and were more willing to publish textbooks in their areas of expertise. Indeed Shelley, Miller, Bloxham and Maxwell would all be authors in Longmans' 'Text-books of Science' series in the early 1870s under the editorship of T. M. Goodeve. Given there were on average only 80 matriculated students[17] in the Department during Maxwell's tenure, the staff list is impressive and suggests why the College always seemed short of money. The average number of matriculated students in the three non-medical departments of King's College during Maxwell's years, excluding evening class students, was 215, very similar to the size of the Marischal College MA cohort.

As an aside, London was not a substantial centre of manufacturing and construction in 1860s Britain. Trade and finance were its strengths, brewing is biggest manufacturing industry. Nonetheless, trade supported a large dock industry and in providing effectively a degree in Engineering from their early years, both London colleges were ahead of most of the other British universities. Outside London, only Glasgow had a Chair of Engineering by 1860. Its occupant then was the notable W. J. Macquorn Rankine, a strong advocate of the importance of scientific principles in underpinning engineering practice and, indeed, the reverse synergy of engineering solutions guiding the development of science.

All matriculated students at King's College were obliged to attend daily chapel at 10 am. Maxwell would have had no issue with this. Indeed his willingness to attend Church of England services was a pre-requisite for the job and he almost certainly attended on the days he was in College. All matriculated students also had to attend the chaplain's divinity class. King's College was not authorised to issue MA or BA degrees for their students but instead offered the AKC, the *Associate of King's College*. There were of course various recognitions and exemptions in special cases but the standard requirement was attendance and satisfactory performance for nine terms, namely three years minimum, for the academic year comprised three terms. The Michaelmas term began in early October and ended just before Christmas; the Lent term began a month later after the middle of January and ended in early April; Easter term began after a break of 10 days and ended towards the end of June. Maxwell and the students then had a break of three months. Fees for Engineering students were £12.17.0 *per term*, excluding books, the compulsory gown and cap and excluding boarding fees for those who wished to make use of the limited living-in facilities. Compare this with Marischal College fees of about £5 *per year*. Students who did not wish to matriculate could enrol in individual classes, the fee for Natural Philosophy being 3 guineas (£3.3.0) per term. Such students were called 'Occasional Students'. The average number of Occasional Students spread over all subjects in the three non-medical Departments was 50.

This was the broad context of Maxwell's King's College teaching, according to the college Calendars. However, the implication that students began in October, attended for nine terms and then departed with their Associateship is completely misleading. The student Registers[18] reveal a different story. Taking a sample of 150 students who were in attendance during the first years Maxwell taught, the average length of time a student stayed was just 4.3 terms. Approximately 40 stayed for just one year, 30 for two years and others for every other possibility. Only a very small minority emerged with the AKC. (Compare this with Marischal College where almost 50% of students completed their four years of study). Not all started in the Michaelmas term either. For example in 1861/62 session, 30 began in the Michaelmas term, 19 in Lent term and 7 in the Easter term. It is hard to avoid the conclusion that King's College was seen from the student perspective as providing not so much a degree as pre-professional further education that opened doors to professions where formal knowledge had more significance than manipulative skill. When a student felt he had acquired sufficient knowledge or when a door of opportunity opened or, perhaps, he could no longer afford the fees, he left.

Applied Science students had a fuller timetable of coursework than most modern University students. The Register recorded an Engineering student's performance in 12 areas each term, usually just with the letters G (good) or VG (very good), though other entries dealt with special circumstances. The areas were: *Divinity*, *Chapel*, *Maths*, *Mechanics*, *Arts of Construction*, *Chemistry*, *Geology*, *Mineralogy*, *Manufacturing Art*, *Geometrical Drawing*, *Surveying* and *Workshop*. *Mechanics* covered Maxwell's Natural Philosophy courses; *Arts of Construction* were not available to first-year students; Photography was a compulsory part of the AKC for final-year students but not recorded explicitly in the Register. Workshop practice for two three-hour sessions per week was part of each term's course. The associated timetable included such complications as some activities every fortnight or activities restricted to certain terms but overall a student's programme involved about 13 lectures a week and 12 hours of practical work a week in four 3-hour afternoon sessions.

Maxwell gave two separate courses, one for first-year students and one for students in second or third years. Each course was taught for three hours a week. With the addition of his evening class, this made for seven hours a week in front of a class (about half his Aberdeen commitment). The pattern of student enrolment on Applied Sciences discussed above suggests that the three single term courses had to be fairly self-contained. The first-year class would have been much the larger class. It was given from 11.30 to 12.30 on Mondays, Wednesdays and Thursdays; the senior class preceding it from 10.15 to 11.15 on the same days. Cyril Domb, a successor to Maxwell at King's College, has written particularly[19] about Maxwell's courses, quoting syllabus details from the annual University Calendars and outlining how his course content evolved. No student notes have been found of his King's College lectures but some examples of the detail Maxwell included in his course have been given in the preceding chapter on his Aberdeen years. Maxwell continued his teaching practice of regularly posing the class a set of 10 questions. Almost 40 sets of these are contained in a notebook[20] now in the possession of the College. These questions were given once a fortnight, Maxwell interleaving the questions for his 'Junior' class and his 'Senior' class in successive weeks. Broadly speaking, it would appear from these questions that his first-year class received a simpler introduction to Natural Philosophy than did his Aberdeen classes. This is not surprising, for his Aberdeen course was given to third year students who had already received a year of mathematics and, in addition, his Aberdeen course was longer.

The first-year class texts at King's College were Galbraith and Haughton's manuals on Mechanics, Hydrostatics and Optics, the same texts Maxwell had adopted at Aberdeen and the same ones his predecessor at King's, the able T. M. Goodeve, had used to support a course that differed from Maxwell's in many details. Maxwell's introductory lectures at Aberdeen and King's College have both been published and examined[21]. They are quite similar. The general coverage of Maxwell's first-year course at King's College was also similar to his Aberdeen course, namely Mechanics and Dynamics, followed by some Hydrostatics and then Heat. The course finished in the Easter term with Optics, at King's College illustrated with demonstrations using an arc lamp or oxyhydrogen lamp. These are the only demonstrations explicitly mentioned in the Calendar but Maxwell did receive an expenses allowance of £15 per annum.

The College had a museum founded upon the George III collection of scientific instruments and apparatus that had been donated by Queen Victoria in 1841 to support the teaching of Engineering. Much of this collection can now be seen in the Science Museum[22] and although it included models of machinery, by 1860 it was somewhat dated. However, additions had been made by the College Council and private donations and the museum was overseen by a curator. 19th century museum practice was to exhibit items in packed glass cases. The idea of a 'hands-on' museum was well in the future and it is likely that the museum artefacts were there mainly to be observed. This was still a significant privilege for the College, since

London had no Science Museum as such in 1860, though it did have the educationally oriented South Kensington Museum. This was a conglomerate institution, mainly a museum of art and artefacts that had evolved from the Museum of Manufactures spun off from the Great Exhibition of 1851 but it also including other components such as a Museum of Education that had spun off from the 1854 Exhibition of Education.

We have to rely on the University Calendars for the contents of Maxwell's senior course, and to the sets of questions still extant in Maxwell's notebook. The Calendar entries look the more impressive. The course began with theoretical lectures on applied mechanics and continued with the motion of an incompressible fluid that included '*solution of questions in heat, electricity, and magnetism*', the analogies he was pursuing in his papers on electromagnetism discussed later on. After a section on waves relevant to sound and light, the course ended with the first principles of astronomy.

When Maxwell had been an undergraduate himself in Edinburgh and Cambridge, he had belonged to student societies that supported discussion on physical topics. The King's College Engineering Society was founded in 1847, the year of inauguration of the Institution of Mechanical Engineers (I.Mech.E.), the second oldest of the British professional engineering institutions. The King's College Society can now rightly claim to be one of the oldest Engineering Societies in the world. It had been vibrant in the late 1850s with a varied programme of lectures[23] before hitting a rocky patch in the early 1860s but it came back to life and in 1864 Maxwell was listed as an honorary President along with the Professors of Maths, Civil Engineering, Manufacturing and Surveying. This suggests that Maxwell had carried his student-friendly persona to London from Aberdeen.

The College's biggest teaching success story during Maxwell's years was its evening classes. These had begun in 1855 offering 15 subjects. The choice rose almost year on year so that in Maxwell's final year 30 subjects were offered. Each class lasted an hour in the week and a course ran over 20 weeks. Students could take a portfolio of courses that included Divinity plus four others and matriculate in the College, for an extra fee, counting the passes accumulated over three successive years towards an AKC. 'Occasional Students' could enrol in one or more classes. During Maxwell's five years at College, an average of about 80 evening class students matriculated annually and almost 500 additional evening class students annually were classed as 'Occasional Students'. Evening class students were given access to the College library. Maxwell's annual contribution was 20 lectures on Experimental Physics, given from 8 to 9 pm on Wednesday evenings, running from mid-October to the end of March, with the one month's winter holiday breaking the course in two. In the advert for his successor, the number of students attending Experimental Physics was put at '*from 20 to 30*'.

For the first two years Maxwell presented a similar, wide-ranging course covering *the effects of heat*, *the measurement of temperature*, *the gas laws and the efficiency of engines*, *conservation of energy*, *basic electrostatics*, *magnetism*, *current electricity and batteries*, *the telegraph*, *radiation*, *optical instruments*, *the eye and eyesight*, *properties of light including its wave nature and interference*, *waves in general*, *optical polarization phenomena*, *physiological optics*, *the measurement of light and colour*[24]. The final subjects bore closely on Maxwell's own colour researches. This was clearly 'experimental physics' well supported by the concepts needed for understanding. The syllabi for the following three years were all different, a reasonable strategy if one is targeting a fixed pool for whom the classes were accessible. In 1862/63 the course concentrated on the *effects of Heat on bodies* and *Electricity and Magnetism*, the 1863/64 course on *Properties of Matter as affected by*

Pressure and Heat – effectively a course on thermodynamics – and the 1864/65 course covered *Magnetism and Electricity*. Cyril Domb has published this last syllabus in full[25]. Campbell and Garnett state that Maxwell '*continued lecturing to the working men*' in the winter of 1865/66, more than half a year after he had retired, but the College Calendar explicitly states that the class will be taken by his successor. Perhaps Maxwell made a contribution without being formally in charge.

One difference in the college from the Aberdeen situation was that larger subjects at King's College employed assistants. During Maxwell's second year, the first 'Lecturer in Natural Philosophy' was appointed, George Robarts Smalley. Smalley had been assistant to Her Majesty's Astronomer at the Cape of Good Hope (Thomas McLear) for five years, then Professor of Mathematics at the South African College and from 1854 in London a respected mathematics master for seven years at King's College School (that had an annual intake of about 400 pupils). He had given the King's College evening class in Mechanics on at least one occasion and been an applicant for Maxwell's post. Smalley assisted Maxwell's day classes for two years before being appointed Government Astronomer at the Sydney Observatory, beginning in 1864. He died in this post aged 48 in 1870. The post of Lecturer in Natural Philosophy was refilled in October 1863 after Smalley's departure by William Grylls Adams, brother of Cambridge astronomer John C. 'Neptune' Adams, whose work the Adams Prize commemorates. Grylls Adams was five years younger than Maxwell and succeeded to his Chair when Maxwell retired in 1865. He kept the appointment for 40 years.

MAXWELL AND THE 1862 EXHIBITION

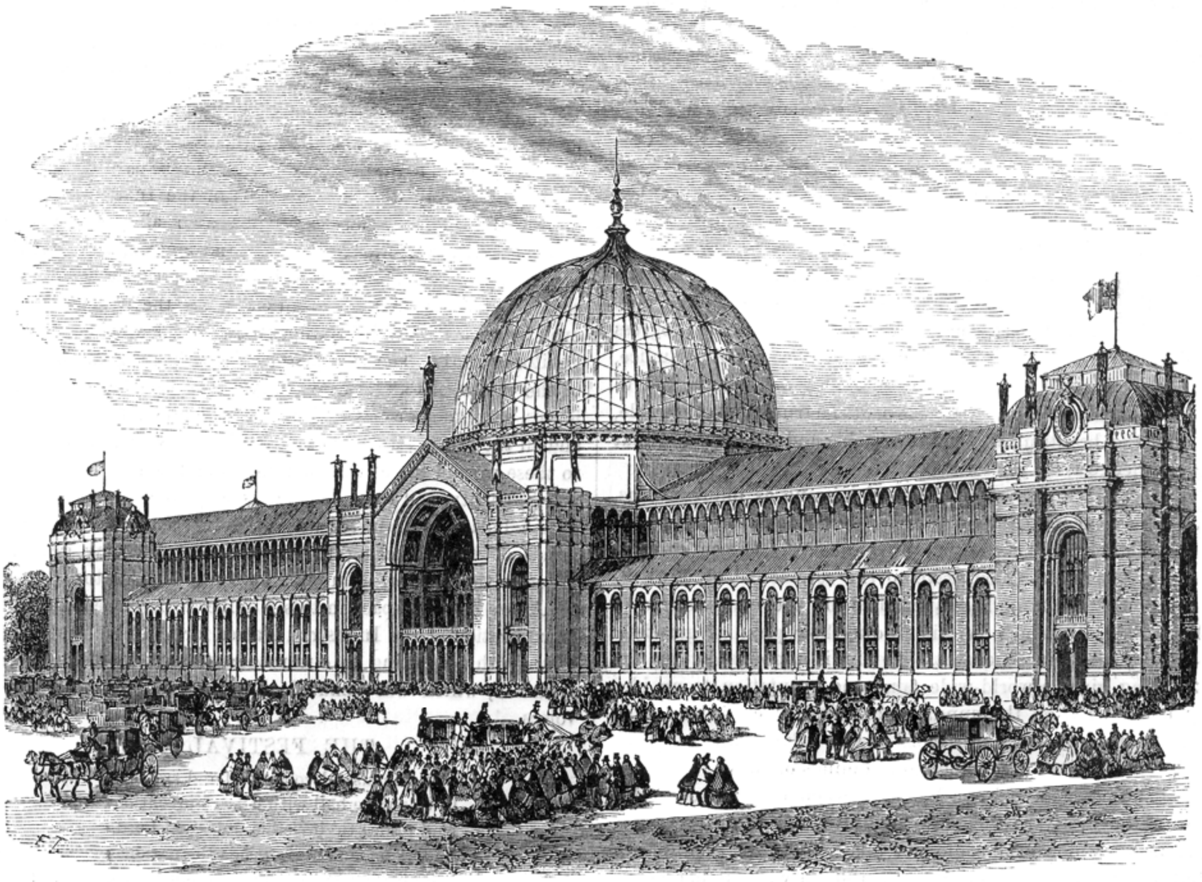

Fig. 3 *View of the exterior of the 1862 International Exhibition from Exhibition Road giving a*

flavour of London in Maxwell's day. He contributed the explanatory account in the exhibition covering the optical instruments exhibited.

Following the great Crystal Palace 'Exhibition of the World's Industry' of 1851 it had been in British minds to hold a sequel a decade later. The success of the London exhibition spurred others such as the Irish Industrial Exhibition of 1853 and the New York Exhibition of the Industry of all Nations, also in 1853, designed to let America measure its industrial strength against that of the rest of the world. Since 1798 France had been holding national Exhibitions of Industry more frequently than every decade and these led to its own International Exhibition in 1855. However, the 1850s had not been a particularly happy decade in Britain. The Crimean war drained national resources from 1853 to 1856; the first Indian war of independence (the Indian Mutiny) made a large psychological impact even though in the end Britain retained control of India. The planned repeat of the Great Exhibition was finally staged in London as The International Exhibition of 1862 in a specially constructed exhibition building in South Kensington [Fig 3]. It ran from 1st May to 15th November, attracting some 6 million visitors. In a number of ways it was considered less successful than the Great Exhibition of 1851: it was in a larger hall that was open longer but attracted fewer visitors per day and barely paid for itself, whereas the Great Exhibition had made a substantial profit. In addition the Queen and Court had not attended its formalities, for in 1862 Victoria was still in mourning for Prince Albert, who had died in December 1861. It was more of an industrial exhibition than its 1851 precursor, with a large Western Annexe occupied by machinery.

One section of the exhibition was devoted to "Philosophical Instruments". Maxwell was involved in the exhibition at least as the author of the explanatory document that accompanied the subsection "Instruments Connected with Light". This summary was published separately but also appeared in the volume that acted as a *Record of the International Exhibition of 1862*[26]. The account is not included in his collected papers but it is a superb example of didactic writing by a gifted expositor. The temptation for many given the task would simply be to describe what the visitors would see. Maxwell goes much deeper. He separates the instruments into their different kinds, clearly explains principles behind their operation, includes key aspects of their historical development, technical difficulties encountered in improving instruments of a given type and describes applications of interest, all in the context of the examples on display.

For example, in his opening section on glass and, in particular, exhibits of parallel-sided glass plates for sextants he describes how he has tested for the flatness of glass using an arrangement we now recognise as Fizeau's fringes. The remarkable aspect of this is that Fizeau only published his method of obtaining fringes in the same year, possibly after Maxwell wrote his guide. Maxwell's experimental knowledge and practice was clearly totally up-to-date. In the next section on an exhibit of lenses, he highlights how cylindrical lenses (on display) exhibit the technology of correcting for astigmatism of eyesight, an aspect realised by G. B. Airy. Following on, his discussion on microscopes explains why the design of microscopes is a much harder problem than the design of a good telescope and how the relatively newly invented binocular microscopes on display give a three-dimensional view with exaggerated relief. This naturally leads on to stereoscopes, although in historical terms it was the stereoscope that gave rise to the binocular microscope. Visitors were encouraged to look at Warren de la Rue's stereoscopic pictures of the Moon, taken using the Moon's libration to provide the necessary parallactic views. The 3D views enabled the viewer to see the Moon as no astronomer could directly, with or without a telescope – an early example of imaging technology extending our ability to explore the natural world beyond the provision of just magnification.

This is not the place to describe all the fields of optics Maxwell covers in his exhibition account. In the next decade Maxwell would become Professor of Experimental Physics at Cambridge and people have wondered why he was chosen for that post, since many of his most outstanding contributions to Physics had been conceptual and mathematical. It is clear, though, that Maxwell's boyhood love of making things grew into a real expertise with laboratory equipment and experimental demonstration. His teaching experiences gave him the opportunity to pursue both aspects and the opportunity to encourage the interests of others and pass on his knowledge. Fourteen years after the 1862 exhibition, under the auspices of the South Kensington Museum of Science, an international 'Special Loan Collection of Scientific Apparatus' was exhibited on almost the same site as the 1862 exhibition. Maxwell wrote the introductory article on the principles and function of scientific instruments in the accompanying handbook[27]. He also wrote the article on "Instruments Connected with Fluids" in the section on Molecular Physics.

Maxwell's exhibition articles provide clear evidence that Maxwell was an accomplished experimentalist.

THE BRITISH ASSOCIATION ELECTRICAL RESISTANCE STANDARD

Maxwell did not present any papers at the BA meeting of 1861 in Manchester but at that meeting the BA set up its subsequently famous 'Committee on Electrical Standards" to which Maxwell would be invited in the following year. For reasons that are about to be given, the first major report of the Committee concentrated on electrical resistance. Maxwell was one of the principal contributors to their first report[28] at the BA meeting of 1863 in Newcastle-upon-Tyne. Their 65 page offering was an important step in the future establishment of the international definitions and standards for the volt, amp and ohm, later defined by the International Electrical Congresses, the first of which was in 1881. The problem was this. Historically measurement of widely used quantities like length, volume, weight, etc. had been encumbered by almost arbitrary standards that varied from nation to nation. Electricity was increasingly pervading industrialised society and it was desirable to avoid a repetition of this state of affairs. Telegraphy in particular was in the process of encircling the world with little regard to national boundaries and an international consensus on electrical units would clearly benefit everyone. At least, that was the altruistic motivation. Commercially, Britain was the leading nation pushing the trans-global telegraphic revolution and her electricians perceived that it was advantageous in terms of quality control, fault-finding and other practical operations to develop a clear and unified system of electrical units. In practice, the ultimate results of this work would affect every man and women in the country and, in due course, everyone in the world. The desirability of an 'absolute' system of units, one where electrical units are as far as possible related to units of other quantities, as opposed to units 'relative' to arbitrary standards, was outlined at the beginning of the report.

Absolute systems were based on firmly established relationships between different quantities. For example, through Coulomb's Law (mid 1780s) relating the force of attraction or repulsion experienced by two charges at a given separation, charge can be defined in terms of force and distance. Current is defined as charge passing in unit time and hence currents defined in terms of force, distance, and time, all basic, pre-defined quantities. The power dissipated in a resistance, which is a rate of doing work, is a product of its resistance and the square of the current passing through it. This brings electrical resistance into view. Finally, Ohm's Law relates the electromotive force (now called the voltage) across a resistor to the value of its resistance and the current through it. So a system of electrical units can be established based upon the electrostatic attraction or repulsion of charges and the underlying system of mechanical units. Using the centimetre, gramme, second (cgs) mechanical system produces the electrostatic system of electrical units, later called the *statcoulomb*, *statamp*, *statvolt* and *statohm*.

There are two issues. First, all the units except the statvolt so defined are unsuitable in their sizes for day-to-day electrical work. Secondly there is an alternative way of going about things that produces a different set of electrical units. Force is also related to the force of repulsion between two coils carrying a given current (as discovered by Ampère early in the 1820s). Starting here, current can be defined in terms of force and distance (the distances involved being the size of the coils and their separation). Charge is now defined through current and time, and so on. This system produces a second set of units, 'electromagnetic units', later called the *abamp*, *abcoulomb*, *abvolt* and *abohm*, only the first two of which are reasonably practical for everyday use. As a short digression it is worth saying that it was Maxwell himself who showed that the ratio of charge measured in electrostatic units and electromagnetic units must equal the velocity of electromagnetic waves in space (e.g. light). In 1868 he published his own completely electrical measurement of this velocity. That, though, takes us to a time in another chapter.

Now aspects of reality enter. Some quantities are more easily measured than others. Current is one of the most easily measured through the interaction of a coil carrying the current and an external magnetic field. For example, the moving coil meter that was the everyday electrical measuring instrument for over a century basically measures current. To measure voltage or resistance their effects are converted into equivalent effects on current. However, to measure current absolutely by this means one needs to know the value of the magnetic field involved, either the Earth's field or one specially created by a magnet inside the instrument. William Thomson had hit upon an alternative doorway into absolute electrical units. The BA report spells out the basis of the method. The theoretical result is that by rotating a thin closed-circuit coil over a suspended small magnet, the magnet is observed to deflect by an amount that depends on the speed of rotation and the dimensions of the coil (all mechanical quantities) and the resistance of the coil. Hence, when the mechanical factors have been determined, including the deflection of the magnet, the resistance of the coil can be measured in absolute units. Once this is done for a standard coil, then using a Wheatstone bridge (promoted by Wheatstone in the 1840s) any other resistance can be measured as a ratio to the standard resistor. With resistance known, then the other quantities can be deduced from the relationships mentioned above. The measuring rod, the balance and the clock, the fundamental measuring tools that underpin all mechanical quantities, can therefore be made to underpin all electrical units.

Maxwell was central to the BA committee's effort. He, Fleeming Jenkin and Balfour Stewart undertook the experiments needed, in King's College. These continued for over a year beyond those reported at the 1863 BA meeting. Maxwell calculated corrections necessary because of the departure of the actual equipment from the theoretical ideal that yielded the relatively simple formulae involved. They all considered at great length minor factors that had to be given attention in order to achieve an accurate result. For example August Matthiessen, who had been appointed Professor of Chemistry at St Mary's Hospital, was especially concerned with the observed variation of resistance with temperature and chose an alloy ('German silver') that would be most suitable as a working standard of resistance.

Appendices A and B by Matthiessen single out this aspect of the work. Appendices C and D by Maxwell and Fleeming Jenkin are a 30-page paper, almost half of the report, including a valuable and innovative section "On the Elementary Relations between Electrical Measurements". In this they introduced in modern notation the method of dimensions for analysing the relationship between units of different quantities, a method that quickly became one of the fundamental tools of basic physics. For example, in the electromagnetic system electrical resistance has the dimensions of velocity, a fact that some telegraph engineers at the time found hard to appreciate, for it was not the velocity of transmitted signals. The second part of their appendices described in detail their King's College measurements. Surprisingly these appendices, too, do not appear in Maxwell's collected works.

Fleeming Jenkin was also responsible for the governor that kept the coil turning at a constant speed and spurred by efforts to improve this device for later measurements, Maxwell was led to reflections on the stability induced by governors, from which he produced a paper in 1868 that is usually quoted as the founding paper of the subject of cybernetics[29]. Another spin-off from the apparatus was Maxwell's own experimental determination of the viscosity of air at varying pressures and temperatures, as indicated in a passing remark to Stokes in 1863. The experiment described above was conducted by rotating the coil at around 6 revolutions per second for some time in an electrically open-circuit configuration and noting the position of the central suspended magnet and then repeating this with the coil in a closed-circuit configuration, during which time a current induced in the coil deflects the magnet. Its deflection was measured by an optical lever attached to the suspension wire. When the coil rotation was stopped, the magnet oscillated back to equilibrium, being damped by the viscosity of the air and internal friction within the suspension. In a fine example of lateral thinking, this gave Maxwell the idea for measuring the viscosity of air by observing the damping of the torsional oscillations of a disk swinging between fixed plates. This method was to form the basis of his 1865 paper to the Royal Society of London describing experimental results that would confirm his 1860 predictions on the variation of viscosity with pressure and temperature. In the BA resistance determinations, one would be hard pressed to find a better example of how academic work on an apparently obscure problem could provide the spark for a diverse range of knowledge and also provide results that had immense practical importance.

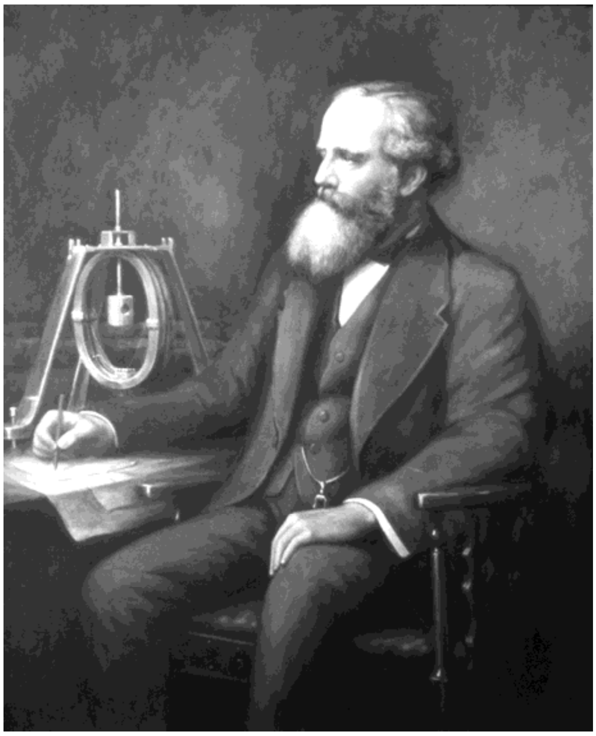

Fig. 4 *James Clerk Maxwell pictured with the spinning coil apparatus that he developed with his collaborators at King's College to establish the British Association standard resistance. This portrait is a copy of the posthumous original owned by the IET. It has been gifted to the James Clerk Maxwell Foundation by Professor David Ritchie and hangs in the Royal Society of Edinburgh's Maxwell Room. Image courtesy of David Ritchie, the James Clerk Maxwell Foundation and the RSE.*

The work continued in 1864, with the 1864 Bath meeting report[30] of the Committee outlining their philosophy that '*every experiment should be made afresh and every element of the experiment should be varied*'. The 1865 Committee report[31] at Birmingham was a mere 6 pages, confirming that the Committee's work had been accomplished (as far as resistance was concerned) but importantly describing the construction of the standard resistors that would form the practical outcome of the whole exercise.

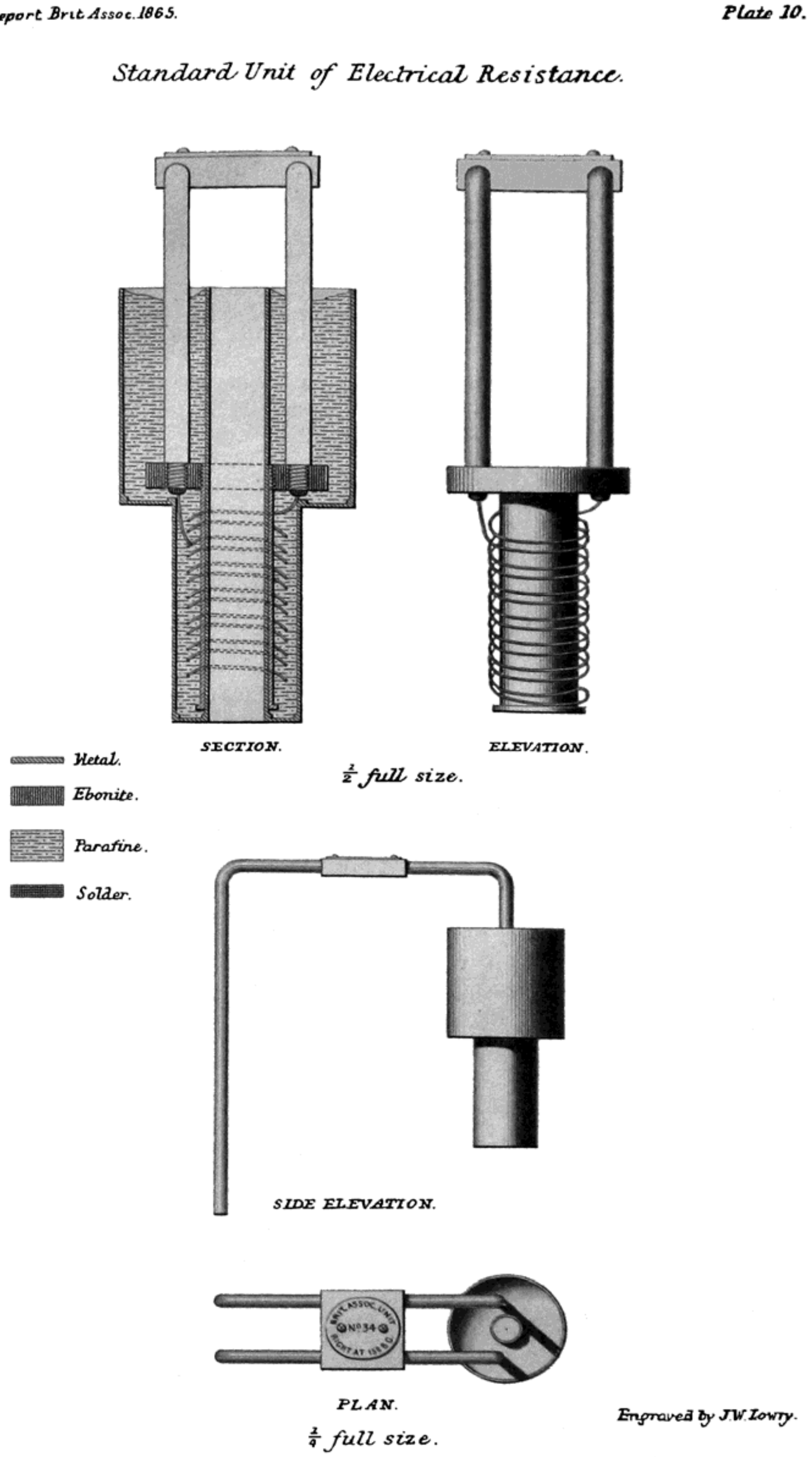

Fig. 5 *Plan of the British Association (BA) standard resistor of 1865, from the 35th report of the British Association, 1865.*

Fig. 5 shows the design of the 'BA standard resistor'. Within the casing, silk covered wire is wrapped around a hollow brass former and the whole embedded in paraffin wax. Thick copper wires take the connection to the outside circuit which is made by dipping them into mercury cups. The resistors are used in a constant temperature water bath and are defined accurate at a specific temperature. A set of ten resistors using different materials was made to investigate aging effects but the preferred wire material for copies was a platinum/silver alloy and the accuracy expected was better than 0.01%. The purchase price of a copy was £2 10s (approximately £250 in 2010 currency). All these fine details and more illustrate what had to be got right if a credible international standard was to be established. Fig. 6 shows a late 19th century water bath with two resistance standards developed from the BA archetype.

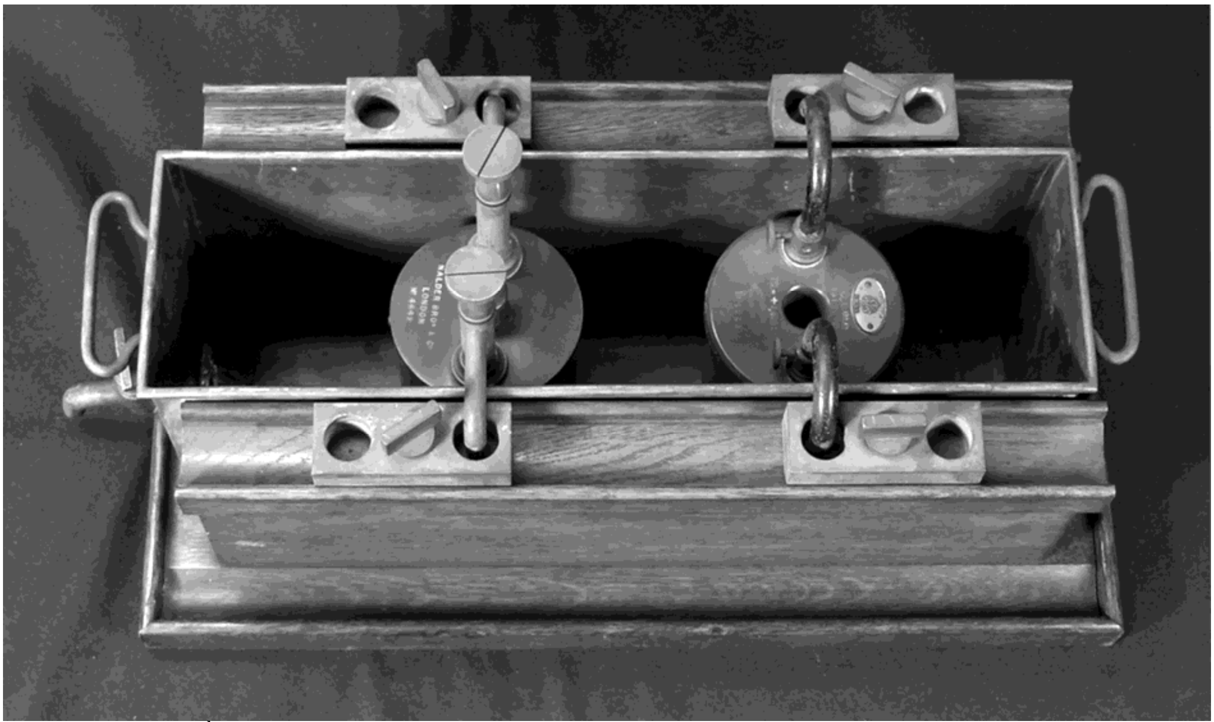

Fig. 6 *Late 19th century standard resistors in a constant temperature bath, from the Natural Philosophy Collection of Historical Scientific Instruments, University of Aberdeen. The central hole in each resistor is for the insertion of a thermometer that could read to 0.1°C.*

The experiments may have been carried out in a King's College University laboratory but the business was a hugely practical matter. Wheatstone, Varley, Thomson, Siemens, Jenkin and Bright on the Committee all had strong telegraphic interests. Telegraphy was the foundation of the electrical engineering profession. Electrical resistance was hugely important, both in connection with the telegraph lines themselves and with the ancillary equipment. The BA unit of resistance defined by the committee was a velocity. The particular German silver coil that was at the centre of the 1863 experiments had a resistance of 1.0762×10^8 m s^{-1}. The BA unit of resistance was defined as 10^7 m s^{-1} and came to be called the ohm, after Georg Ohm, an electrical pioneer who had died in 1854. (Before the 1860s were out, today's symbol Ω for ohms had been introduced by William H. Preece, a former pupil at King's College by co-incidence, and later to rise to Engineer in Chief for the Post Office in Britain's nationalised telegraph and telephone service.) Through Maxwell's contact with the instrument making firm of Elliott Brothers, particularly with Carl Becker, secondary standard coils were carefully made and calibrated with reference to the BA master coil. Copies were distributed in the first instance to Directors of Public Telegraphs in 11 countries and to other bodies. One result was that electrical resistors in ohms were spread rapidly among the telegraphic community and from there outwards. Once the unit became widespread its incorporation into the international electrical standards was not surprising, though its definition has changed more than once.

One other legacy of this work is that thanks to the involvement of scientific men in the enterprise, the system of electrical units was tied from the very beginning to the metric system of mechanical units. It has taken the whole of the 20th century to persuade most of the world to use metric units for commerce and everyday life, and the task is not yet quite complete in the 21st century, but electrical units have needed no change, for they have been universal and tied to the metric system from the beginning. For example, the unit of electrical power, the Volt-Amp, is identical to the metric mechanical unit of power, the Watt.

The corollary to this episode is that it involved particularly careful work extending over two years by Maxwell and colleagues to determine the absolute value of the resistance of the master coil in absolute units to the required precision. No-one who wanted to reproduce as exactly as possible one ohm of resistance could contemplate such effort. One of the secondary standards made by the BA was a column of mercury representing one ohm, and for practical purposes it was decided by the International Electrical Congress in Chicago in 1893 to re-define the ohm as the resistance of a specified column of mercury at 0°C. The emphasis moved in the 20th century to considerations of how a standard resistance could be defined so that it could be reproduced and used most accurately in comparisons. This lead to the abandonment of the mercury column and the adoption of a more erudite definition involving the quantum Hall effect that was made the international standard in 1990. The redefinitions were intended to be backward compatible so that within the physical uncertainties of the old standards they maintained the value of the ohm as that specified by the original BA Committee. It practice they didn't quite succeed in this aim.

MAXWELL ON ELECTROMAGNETISM

Maxwell's work on electromagnetism is now seen to outshine all his other efforts, but it was certainly not so in his day. It was while at King's College that he finally worked his way through the mist of uncertainty that had obscured his vision until then, revealing a new landscape in which were situated the complete laws of electricity and magnetism. Maxwell's laws were formulated in terms of differential equations (an important difference from some earlier work); the quantities involved were electric and magnetic fields; the laws contained some addition to previous knowledge; the laws predicted the possibility of transverse electromagnetic waves that travelled at the speed of light. By implication, Maxwell took it that light and radiant heat were therefore electromagnetic waves. It would take another quarter of a century before experiments were directed at the now obvious question of whether other electromagnetic waves existed or could be generated. Maxwell would no longer be alive to hear the answer.

Maxwell's work was a visionary effort. After starting with William Thomson at least alongside him, there was no-one leading him through, no-one at his heels threatening to discover a few months later what he himself found. Even Maxwell's own involvement in the issue is a long story, beginning at Cambridge, running through his Aberdeen years, when the issue was clearly gestating in the background of his other work[32], to his major papers produced at King's College. Electricity was not, and is not, an easy science. In Maxwell's own words on the state of the subject as he found it in 1855: "*In order therefore to appreciate the requirements of the science, the student must make himself familiar with a considerable* *body of the most intricate mathematics, the mere retention of which in the memory materially interferes with further progress.*"[33] Many a student since would share this sentiment. To appreciate the King's College work, a brief introduction to the mist Maxwell was immersed in is necessary. It must be said that the next few paragraphs are but a very brief outline.

Ask the question 'what is electricity?' or 'what is magnetism?' and even today no-one will give a straight or simple answer. There isn't one to give, for the subjects are intrinsically complex and interlinked. Some connection between them had been suspected for years but it was Oersted's demonstration in 1820 that a steady electric current (namely, a steady movement of charge) produced a steady magnetic field, which initiated the concept of electromagnetism. This discovery was soon followed in 1821 by Faraday's that a magnetic field acting on a current-carrying conductor exerted a force on the conductor that could, in a suitable arrangement, make the conductor rotate. This was '*Faraday's motor*', though it was not a device that could provide any useful power. A decade on, Faraday discovered electromagnetic induction, the property that a changing current in one circuit can induce a changing current in a neighbouring circuit. Faraday's experimental researches on electricity and magnetism were extensive, driven by his wish to explore new phenomena and to understand what these phenomena were about. For understanding one needs a grasp of underlying concepts and Faraday's visualisation slowly crystallized in terms of his own concepts: the magnetic field and the electric field[34]. In this picture, the causes of electromagnetic phenomena are electric and magnetic fields. Bodies in a field react with the field that is present where they are in a way that depends on the strength and direction of the field. The source of the fields that influence surrounding space are electric charge and currents. (Magnetic poles, it turns out, are generated by currents). Because this is the picture drawn nowadays in all textbooks on the subject, it seems to us a natural description but the reason it seems so natural now is down to the work of Maxwell.

Faraday was only one of many experimenters and synthesisers of the phenomena of electricity and magnetism in the first half of the 19th century. Their story is a long one, covered in varying detail in textbooks, in histories such as that of Darrigol[35], in articles and in Maxwell's cited biographies. Well-known laws of electricity and magnetism such as those of Ampère, Biot-Savart, Lenz and others are a recording of this work but Faraday's researches were the explicit source of Maxwell's inspiration. To continental investigators, Faraday's ideas were mere hand-waving metaphor, devoid of depth and, ultimately, reality. Charge was the source of electrical phenomena and charges influence each other at a distance, via Coulomb's law and, in more complicated circumstances, with a dependence on their motion. Interacting points made for a mathematical basis of electricity and magnetism (such as laid out by Wilhelm Weber) and set the paradigm within which quantitative formulae were developed. Maxwell had digested Weber's treatise on electrodynamics and was highly respectful of his work, summarising its foundations in his own 1855 paper. Notwithstanding, it was Faraday all the way for Maxwell, particularly in terms of the *processes of his reasoning.* It is hard to visualise the effects of moving interacting points. 'Lines of force' are easier to visualise and the electric field, for example, is simply defined as the force on a unit charge at a given location. An analogous definition works for magnetism. Place a magnet under a sheet of paper and sprinkle iron filings over the paper and it is not hard to visualise magnetic field lines. Faraday and Maxwell might have argued that the filings make the field lines visible, in the way that a brass rubbing makes visible the corrugations in a sheet of plane paper smoothed over a brass plaque.

For Faraday and Maxwell, field lines weren't just visualisations; field lines had properties. For example, they never crossed, they repelled each other and, to invoke a more modern attribute, it took energy to squeeze them together. A charge interacted with the field at the charge's location, not with other charges through some 'spooky action-at-a-distance'. In placing a charge somewhere one altered the field everywhere. When magnetic field lines within a conducting loop were changed, then a current was induced in that loop. Maxwell's self-appointed task was to express the properties of these fields in mathematical terms that embodied the known behaviour of interacting electric and magnetic systems.

It is easy in principle to follow the line of reasoning that if fields exist, then space must be filled with a medium whose properties reflect those of the fields we observe everywhere. It is not so easy in practice to follow the implied mathematics. Maxwell's first major paper on the subject, written in 1855 and using mathematical techniques developed by William Thomson to discuss the flow of heat, made the fully quantitative analogy between electrostatic and magnetostatic field lines and the hydrodynamic flow of an imagined incompressible medium that carried their influence. It's just an analogy, Maxwell emphasised, the basic idea of which came from William Thomson. The analogy between heat and electrostatic attraction is not obvious but is at the heart of Maxwell's entry into the field. Heat is conducted away from a small source so that the energy per unit area falls off as the inverse square of the distance from that source. Surfaces of constant temperature are spherical surfaces around the source. The analogy is that the electrostatic force at a distance from a small charged object changes as the inverse square of the distance away; equi-potential surfaces are concentric spherical surfaces. Maxwell argued that, at least as far as the mathematics is concerned, we can consider electrostatic attraction and heat flow as analogous. Heat conduction is imagined as the flow of energy through the interaction between neighbouring parts of a medium so this is suggestive that electrostatic interactions can be modelled by flow. From heat flow Maxwell moved quickly to *an imaginary fluid* and so began what would turn out to be a long-running analogy between electrical phenomena and incompressible fluid flow. Maxwell was at pains to point out that his approach was not offered as an explanation: "*I do not think that it contains even the shadow of a true physical theory; in fact, its chief merit as a temporary instrument of research is that it does not, even in appearance, account for anything*"[36]. Perhaps not, but as a fruitful idea it had more to offer. Many people have since implied that Maxwell was trying to explain electromagnetism in mechanical terms. As he himself said repeatedly, he was not.

At King's College he returned to the analogy in 1861 and 1862, now making it sufficiently involved to represent interlinked electrical and magnetic phenomena. His model of the mechanics of the medium imagined vortices, representing the magnetic field, between which were 'idlers' (a mechanical concept referring to free wheels in a gear train) representing the electric field, that allowed neighbouring vortices to rotate in the same direction. The idlers could slip between the vortices with some resistance[37]. It all sounds almost bizarrely clunky to a modern ear yet our description of a current passing through a magnetised material as involving the passage of electrons past spin up and spin down atoms involves philosophically very similar concepts, worded in a different language. Unlike Maxwell, our language claims to describe what is really there in a magnetic material. Maxwell was trying to describe the constituents of the fields themselves but it is not as unlikely as it may seem at first that Maxwell did come up with the correct mathematical description of electric and magnetic fields. He was led down this path by trying to put into mathematical form already established experimental results. This is not the place to go into detail but it is the place to describe one of his great strokes of insight embedded within these papers, the revelation of a missing piece in everyone's understanding of electricity.

Electric current is traditionally described as the rate of flow of charge. In modern units, a current of one ampere is a flow of one coulomb of charge per second. Through a suggestion thrown up by his analogy, Maxwell realised that the concept of current had to be extended. Currents, he said, were also caused by a rate of change of the electric displacement field (**D** in today's standard notation). This term had to be present in the equations alongside the traditional 'conduction current'. Maxwell called it 'displacement current'. Modern textbooks introduce the concept as if it were almost 'obvious' but this was not so in Maxwell's time. He was led to include it by a consideration of what happens to charges in a dielectric material when an applied electric field is changing. Since the displacement field reduces to the electric field (within a constant) in a vacuum, displacement current must also exist in a vacuum, or as Maxwell would have put it, in the medium that supports fields in a vacuum. With the inclusion of displacement current, then some manipulation of the differentials in his mathematics that can be done nowadays in only a few lines using modern vector notation, he was able to show that electric and magnetic fields could support waves obeying a simple wave equation, even in a vacuum. Moreover, their speed of propagation is given by the ratio of the measures of charge in electrostatic and electromagnetic units, a constant known then to be close to the velocity of light, but which needed further, more precise, measurement. Also, the waves are transverse waves that can exhibit the full range of polarisation phenomena observed in optics. In Maxwell's own much quoted words "*we can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of the electric and magnetic phenomena*".

Without the concept of displacement current, no waves are predicted by the remaining equations. The displacement current depends on the property of the medium in which the fields occur and hence can't be represented by any property of sources alone in the action-at-a-distance formalism. Maxwell's insight reminds one of the insight of Einstein who recognised that mass wasn't the only source of gravity, as it is in Newtonian physics, but that gravity has other causes in space. Without that extension of an apparently fundamental understanding, there would be no gravitational waves. Without Maxwell's extension of the idea of current, there would be no electromagnetic waves in electromagnetic theory.

Maxwell's final stroke of genius (to use a justifiable cliché) in relation to this work was to sweep away all use of the mechanical analogy, presenting electric and magnetic fields as existing in their own right, obeying the relationships that he made clear in his 72-page, multi-part paper presented to the Royal Society of London in 1864 and published in 1865[38]. Maxwell does think of space as filled with a medium '*capable of receiving and storing up two kinds of energy*', for example, but there is no mention of specific mechanism, no vortices, no lines of idlers. "*In the present paper I avoid any hypothesis of this kind*" he said, echoing Newton's famous Latin phrase '*hypotheses non fingo'*. This is essentially the modern view that the electromagnetic field is a fundamental entity of nature, not explicable in other terms. His statement is essentially: sources generate fields, fields obey the following laws "*the general equations of the electromagnetic field*" as Maxwell called them, now known as *Maxwell's equations*. The mist had cleared, the landscape revealed. Physics had been introduced to a new world, or at least a new paradigm, but it was one that very few of his contemporaries could see clearly in. There were some extenuating circumstances. For example, the *general equations* were not in a form or a notation that today's students of electromagnetism would recognise easily. In addition, Maxwell had emphasised the field descriptions in terms of scalar and vector potentials. This was mathematically elegant but his successors found that representing the field equations directly in terms of the electric and magnetic fields themselves (as usually presented in modern textbooks) was more fruitful for their application[39]. This development had to wait until the work of Oliver Heaviside was published in 1885.

Maxwell presented new evidence for the idea that light and radiant heat are electromagnetic waves, linking the previously separate studies of electricity, magnetism and optics. This wasn't too big an idea to swallow since others, Faraday in particular, had felt there might be a connection. Over his years at King's College, Maxwell continued his correspondence with Thomson but in so far as can be judged from surviving letters, it was all in relation to experiments and apparatus, not to his 'Dynamical Theory of the Electromagnetic Field'. In fact it is hard to pin down any immediate influence of his 1865 paper because eight years' later he published 'A Treatise on Electricity and Magnetism'[40] that included a major exposition of the whole field and some reformulation and expansion of his own ideas. The 'Maxwellians' that promoted his ideas later in the century drew their inspiration from the Treatise rather than the King's papers. Thomson and Tait were significantly involved in corresponding with Maxwell over this production – it was in many ways the sequel treatise to their own 'Treatise on Natural Philosophy' that dealt with kinematics, statics, dynamics and related topics - but their attitudes to it differed markedly. At least for a couple of decades after Maxwell's 1865 paper, and arguably for the rest of his life, Thomson considered that Maxwell had wandered into the wilderness; Tait considered the Treatise on Electricity and Magnetism revolutionary in the very best sense. In the Treatise, Maxwell wanted to lay out more clearly and more fully his locally acting field theory, in contrast to the action-at-a-distance theory still promoted, particularly on the continent. Maxwell had seen further than others, but he himself would have acknowledged it was because he was sitting on the shoulders of Faraday. The influence of Maxwell's ideas gathered pace slowly[41] after the publication of the Treatise, but that takes us far from his King's College years.

MAXWELL ON GASES AND OTHER TOPICS

There is a breed of scientist who spots an opening to a little explored field, enters it and picks the low-lying fruit before moving on to new pasture. This was not Maxwell's way. He had wide interests, it is true, but his interests were deep. He brought with him from Cambridge and Aberdeen research interests in colour, in optics, in mechanical systems, in electricity and magnetism, in the kinetic theory of gases. He developed all of these while at King's College without finishing with any of them. His final two years' research at King's College was almost entirely occupied with electrical matters. As he was contemplating resignation from his Chair, he began to take up again his work on the statistical treatment of gases, aspects of which he continued until the end of his life. It was the area he was best known for in his last decade.

As a closure on his 1860 predictions that the viscosity of gases would be independent of density and would depend on temperature in a way that was determined by the inter-molecular force law, Maxwell began his own experiments, carried on in the attic of 8 Palace Gardens Terrace. In a letter to Tait in early March 1865 he mentioned that he had been set back a month by an implosion of his glass vacuum vessel. By the end of the month he had begun measurements in earnest using his method of observing the damping of a stack of torsional disks interleaved between a stack of fixed disks. He was able to present the analysis of the experiment and his results to the Royal Society of London in November 1865 and read his much postponed Bakerian Lecture to the Society in February 1866, now entitled 'On the Viscosity or Internal Friction of Air and Other Gases'. This was Maxwell's *experimentum crucis* in the field. The results did more than any other single paper to establish him as the leading 'molecular scientist' of his age. In 1866 he followed this up with another long and significant paper on the dynamical theory of gases, re-working some of the controversial aspects of his 1860 paper, but this again takes us beyond his King's College years. Francis Everitt[42] among the Maxwell biographies provides the best summary account of this aspect of his work. Fuller accounts with supporting documentation have been published by Garber, Everitt and Brush[43] in their two volumes that cover all of Maxwell's related science.

One theme of Maxwell's interests that is usually underplayed is his continuing interest in elasticity and mechanics. His first extensive paper on the subject (*On the Equilibrium of Elastic Solids*) was read to the Royal Society of Edinburgh while he was still a teenager, before he went to Cambridge, and published by the RSE in 1853. This largely mathematical paper includes an explanation of the stress patterns seen in polarised light shone though slabs of glass, a subject that Maxwell had experimented with at length. Maxwell followed this by another mathematical paper written at the end of his Cambridge undergraduate career *Transformations of Surfaces by Bending*. His strong background in the mathematics of mechanical systems played an important part in seeing through his mechanical analogy of electromagnetic phenomena. At King's College, he turned his attention to the graphical solution of mechanical problems and wrote the first of several papers on graphical statics. Maxwell developed the generality of a method that Rankine had introduced in 1854[44]. He laid out clearly, for the first time, the mathematics underlying the reciprocal relationship between forces in a framework (when these are not over-determined) and the polygons of forces at each intersection point of the members of the framework. At an intersection the lines of force (tensions or compressions of the frame members) all come to a point and sum to zero. The forces when drawn out on paper as vectorial lines form a closed polygon. The piecewise polygonal framework and the composite of the polygons of forces form reciprocal figures. The geometry of the reciprocal figures enables the stress in each member to be determined graphically when the framework is suitably supported.

He followed this up after he left King's College with two further papers extending the concepts. The final paper on this subject *On Reciprocal Figures, Frames, and Diagrams of Forces* published in the Transactions of the Royal Society of Edinburgh in 1870 earned him the Keith Prize of the RSE. The prize was a gold medal and sum of around £50 awarded biennially for the best paper in science published by the RSE. Maxwell did not win many prizes or secure many awards during his lifetime but the Keith Prize rightfully added him to a list of recipients that already included Brewster, Forbes, Graham, Rankine, Boole, Thomson, Piazzi Smyth and Tait, a list strongly biased towards Scots but nonetheless a list of outstanding scientists[45]. E. J. Routh's widely used 2-volume *Treatise on Analytical Statics*[46] devotes a whole chapter to reciprocal figures, crediting Maxwell with supplying the underlying theory. The algebraic solution of such problems using computer packages has now completely replaced graphical methods.

MAXWELL'S DEPARTURE FROM KING'S COLLEGE

London was undoubtedly a hub for scientific intercourse and in various ways Maxwell made good use of his time at King's College. He particularly involved himself with the Royal

Society of London, including refereeing papers in much more detail than necessary simply to sanction them for publication in the *Transactions*[47]. In April 1864, John Tyndall asked if he would join the Philosophical Club, a group of leading Fellows pledged to promote the work of the Royal Society. However, looking over the whole of Maxwell's scientific output, he published little joint research. His work on the BA standard of resistance carried out at King's College was his principal collaborative undertaking[48]. Only the few British Association committee reports included in his collected works have a joint author, out of a hundred or so publications, though Maxwell certainly corresponded with his contemporaries on issues he was gestating. His four books published in his lifetime, on heat, on electricity and magnetism, on matter and motion and on the collected works of Henry Cavendish, were his alone. His work on the stability of Saturn's rings was, arguably, a fifth book and not a paper. It is hard to resist the conclusion that Maxwell's inspiration came from deep within himself.

London was also a magnificent opportunity to widen one's social life and this aspect of the capital Maxwell does not seem to have drawn on much. It's true that absence of evidence is not convincing evidence for absence but it is certainly the case that neither by his biographers Campbell and Garnett, who cited a large number of Maxwell's letters, nor in other published correspondence are the Maxwell's recorded as attending a ball, a concert, a play, a literary reading, or any social relaxation in the city. Nor is it mentioned that they had any soirées at 8 Palace Gardens Terrace. Of course they were not monastic but the fact was that Maxwell spent the formative years of his youth in the country and was at heart the country laird that he was now in name. Glenlair was his real and his spiritual home. City life was business life, not home. This was reflected in the leased nature of 8 Palace Gardens Terrace. Katherine was not a socialite and neither was Maxwell, though given the invitation undoubtedly he would have been charming and erudite.

Maxwell resigned his King's Professorship in February 1865, mid-session. The Easter term classes in 1865 were taken by his successor. He made a passing comment in a letter of 1866 that he could undertake more experiments and theorising now that he had no public duties. This was obvious in a way, but suggests that the motivation for his resignation was at least in part the feeling that his research was building to such a level that it needed his full-time commitment. Given all he had already achieved while at King's College and that he had in mind to produce a treatise on electricity and magnetism, then that was almost certainly a major reason for his decision. Another less obvious contribution may have been the way things were going at the College. Maxwell took the King's College job because he valued the experience of teaching. Yet he had now a much narrower range of students than he had encountered at Aberdeen and even at Cambridge. He was, in effect, teaching mainly engineering students. Moreover, most did not last the course, for their priorities lay elsewhere. His students' decided ambitions were echoed in the utilitarian ethos of the College as a whole. If Maxwell's satisfaction in his teaching was declining, then it made good sense to re-group his resources. Already he was doing less than earlier and there was a competent second in command in the shape of Grylls Adams, fully capable of stepping into his shoes in front of his classes. Resigning his post was the obvious move, given all the circumstances.

There may also have been unspoken reasons. For example the centenary historian of the College asserts that there was a marked loss in quality of the student intake to the Department of Literature and Science from the mid eighteen fifties, resulting in cohorts that could not follow the lecture courses. Possibly this situation affected Applied Sciences too. Maxwell's successor was offered the post at a significantly reduced salary[49], perhaps a sign that the

College could scarcely afford the Lecturer in Natural Philosophy who was appointed during Maxwell's tenure. Maxwell himself may have been faced with a similar salary cut. We do know that one consequence of the fusion of the Aberdeen colleges was that Maxwell would continue to receive his full Aberdeen income for life, adding to his financial independence. Any continuing concerns over Katherine's poor health would have made Glenlair much more attractive than central London[50]. Into the bargain, Maxwell and Katherine had been planning an enlargement of Glenlair house for some years and hence the move from London may have been encouraged by Katherine and foreseen for much longer than Maxwell ever confessed[51]. We're not likely to weigh correctly all the factors that might have influenced their decision. Clearly, though, Maxwell had not lost his intellectual interest in teaching, for it would be well after leaving King's College that he produced his long-running teaching textbooks.

As far as Maxwell's research was concerned, this time was not a natural break for any of his interests, even those on colour vision. These issues are taken up in other chapters. In fact Maxwell spent the winters of 1865 and 1866 at 8 Palace Gardens Terrace and the early months of 1868. However, these were not his King's College years. It is tempting to speculate on a few counterfactual scenarios in his life. If Maxwell had followed up less diffidently Stokes' comment in 1857 suggesting Fellowship of the Royal Society of London, it's hard to see how the Aberdeen Royal Commission could have preferred David Thomson had Maxwell been a Fellow by 1859; it would have made it less likely that P. G. Tait would have been preferred at Edinburgh in 1860. (Tait never became an FRS, though that was the Royal Society's loss). Had Maxwell settled in Edinburgh, would he have resigned in 1865 to retire to Glenlair? Possibly not, but then we may not have had the Treatise on Electricity and Magnetism as it emerged and Maxwell's Cavendish contributions. How Maxwell's life actually turned out is related in other chapters.

Notes & References

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[1] *Encyclopaedia Britannica; A Dictionary of Arts, Science, and General Literature* (Adam & Charles Black, Edinburgh, 1875) 9th ed'n, vol. XIV, p821, 1882.

[2] In the 34-page, double column, article on "London", op. cit. ref. 1, 'Higher Education' merits only a single modest paragraph, p835.

[3] This issue and the reforms that came later in the 19th century are discussed more fully in Geoffrey Cantor, *Quakers, Jews and Science: Religious Responses to Modernity and the Sciences in Britain, 1650-1900*, (OUP, 2005).

[4] F. J. C. Hearnshaw, *The Centenary History of King's College London 1828-1928*, (George Harrap & Co. Ltd., London, 1929), discusses the foundation and early history of King's College. However, his brief and ill-founded comment on Maxwell (discussed at length by Cyril Domb, op. cit. ref. 19) does not enhance his reputation as a historian.

[5] In 1860, London's *Daily News* published the official results of the entrance exam of the Civil Service of India, competed for by young men around 20 years old who had a University Degree, or equivalent. Graduates of Oxford and Cambridge dominated the list of some 80 strong, with Dublin and Belfast making up significant numbers. The four candidates from Aberdeen all came in the top half, three in the top 20%; the four candidates from King's

College, London were all in the bottom quarter. Daily News, London, 22nd August, 1860. One would need a longer run of data (not readily available) and more background to establish a trend but the figures are suggestive that King's College was still finding its feet or, more positively as suggested in the text, aiming to provide an education with a different emphasis.

[6] Lyon Playfair's lecture is reported at length in John Tallis *History and Description of the Crystal Palace and the Exhibition of the World's Industry in 1851*, (London Printing & Publishing Co., n.d. [1852]) vol. II, pp 194-200 in which he explicitly cites University College and King's College '*as productive of much good …… but their instruction in science terminates just where the industrial colleges of the continent begin*'.

[7] King's College Council Minutes, 1860, Ref: KA/C/M, p231, includes the printed specification for the Professorship of Natural Philosophy; p232 lists the other candidates as *Rev. A. Power, R. B. Clifton, G. R. Smalley* and *A. H. Green* and the Council's decision.

[8] Op. cit. ref. 7.

[9] Charles Fabre *Traité Encylopédique de Photographie*, (Gauthier-Villars et Fils, Paris, 1889-1906).

[10] W. D. H. [Willem Hackmann], "Thomas Sutton Panoramic Camera Lens", in Sphæra No. 8, Newsletter of the Oxford Museum of the History of Science, 1998. http://www.mhs.ox.ac.uk/sphaera/index.htm?issue8/articl7 .

[11] J. C. Maxwell "On the Theory of three Primary Colours", Notices of the Proceedings at the Meetings of the Members of the Royal Institution of Great Britain, vol. III, May 17, 1861, pp 370 – 375; reproduced in W. D. Niven, The Scientific Papers of James Clerk Maxwell, (CUP, 1890), vol. 1 (hereafter referred to as SP1), pp 445-450.

[12] Ralph M. Evans "Maxwell's Colour Photograph", Scientific American, vol. 205, pp 118-128, (1961).

[13] Lewis Campbell & William Garnett, *Life of James Clerk Maxwell*, (MacMillan & Co., London, 2nd edition, p177, 1884).

[14] *The Calendar of King's College, London for 1860-61*, p113. The same wording is in the Calendars of other relevant years.

[15] Hosking was replaced by Prof. Robert Kerr, an Aberdonian who had been a private student of Natural Philosophy at Marischal College in 1836-37, first President of the Architectural Association and became a respected authority on domestic housing.

[16] "The Charles Loudon Bloxam Papers" are deposited in the British Museum, additional manuscripts 81280-81289.

[17] The King's College Calendars, assembled each summer, contain a report for the previous year prepared in April that includes the numbers of matriculated students in each Department.

[18] "King's College Applied Science Register No. 1 (1857-1869)", King's College archives KA/SRB/7.

[19] C. Domb, "James Clerk Maxwell in London 1860-1865", Notes and Records of the Royal Society, vol. 35, pp 67-103, (1980).

[20] James Clerk Maxwell, "Manuscript notebook, vol. 1", King's College Archives, ref: GB 0100 KCLA Maxwell.

[21] P. M. Harman, *The Scientific Letters and Papers of James Clerk Maxwell*, vol. I (hereafter referred to as SLP1), (CUP, 1990), pp 419-431 and pp 662-674.

[22] Alan Q. Morton and Jane A. Wess, *Public & Private Science: The King George III Collection*, (OUP, 1993).

[23] W. O. Skeat, *King's College London Engineering Society 1847-1947*, (King's College, London, 1957).

[24] King's College Calendar op. cit. ref. 14, pp 268-270.

[25] C. Domb, op. cit. ref. 19.

[26] J. Clerk Maxwell "Instruments Connected with Light", pp 502-507 in *Record of the International Exhibition 1862*, (William Mackenzie, London, 1863).

[27] J. Clerk Maxwell "Special Considerations Respecting Scientific Apparatus", pp 1-21 and "Instruments Connected with Fluids", pp 87-92 in *Handbook to the Special Loan Collection of Scientific Apparatus 1876*, South Kensington Museum Science Handbooks, (Chapman and Hall, London, 1876).

[28] Professor Wheatstone, Professor Williamson, Mr. C. F. Varley, Professor Thomson, Mr. Balfour Stewart, Mr C. W. Siemens, Dr. A. Matthiessen, Professor Maxwell, Professor Miller, Dr. Joule, Mr Fleeming Jenkin, Dr Esselbach, Sir C. Bright, "Report of the Committee appointed by the British Association on Standards of Electrical Resistance" pp 111-176, in *Report of the Thirty-Third Meeting of the British Association for the Advancement of Science; Held at Newcastle Upon-Tyne in August and September 1863*, John Murray, 1864. This and subsequent reports were the only papers published in the joint names of Wheatstone and Maxwell. Wheatstone was in name Professor of Experimental Philosophy at King's College London for 41 years. He was almost 30 years older than Maxwell but although they shared an interest in matters electrical, mechanical and optical it seems they did not collaborate. Wheatstone gave no lectures for most of his tenure, didn't attend BAAS meetings and it is likely that he wasn't paid by the College, since payment was related to number of students taught. Wheatstone had his own personal laboratory equipment and his own library (both of which he donated to King's College in his will) but his post was largely honorific and by 1860 his focus was in the commercial world of telegraphy. However, the association did bring prestige to King's College and academic credibility to Wheatstone.

[29] J. Clerk Maxwell "On Governors" in W. D. Niven, SP2, pp 105-120.

[30] "Report of the Committee on Standards of Electrical Resistance", pp 345-367 in *Report of the Thirty-Fourth Meeting of the British Association for the Advancement of Science; Held at Bath in September 1864*, (John Murray, 1865).

[31] "Report of the Committee on Standards of Electrical Resistance", pp 308-313 in *Report of the Thirty-Fifth Meeting of the British Association for the Advancement of Science; Held at Birmingham in September 1865*, (John Murray, 1866).

[32] Although Maxwell published no papers on Electricity and Magnetism while at Aberdeen judging from some of his letters he was clearly thinking about the subject following his 1855/1856 papers 'On Faraday's Lines of Force'. His letter to Faraday in November 1857 is published in P. M. Harman, SLP1, pp 548-552 and in a letter to his friend R. B. Litchfield, pp 508-509, he commented *I believe there is a department of mind conducted independent of consciousness, where things are fermented and decocted, so that when they are run off they come clear.* His decocted thoughts on electromagnetism appeared soon after he settled in at King's College.

[33] James Clerk Maxwell, "On Faraday's Lines of Force", in W. D. Niven, SP1, p155, reprinted from the Transactions of the Cambridge Philosophical Society, vol. X, part I.

[34] This is oversimplifying the complex issue of Faraday's own changing conceptions on electric and magnetic fields, for Faraday did not use the term 'field' until 1845, though he had earlier talked of magnetic lines of force.

[35] Olivier Darrigol, *Electrodynamics from Ampère to Einstein*, (OUP, 2000).

[36] James Clerk Maxwell, op. cit. ref. 33, p207.

[37] James Clerk Maxwell "On Physical Lines of Force", pp 451-513 in W. D. Niven, SP1; reprinted from Phil. Mag. vol. XXI, pp 161-175, 281-291, 338-348 (1861) and Phil. Mag. vol. XXII, pp 12-24, 85-95, (1862).

[38] A Dynamical Theory of the Electromagnetic Field", pp 526-597 in op. cit. ref. 33

[39] See Bruce J. Hunt, *The Maxwellians* (Cornell University Press, New York, 1991) for an extensive account of how Maxwell's ideas influenced the next generation of electrical researchers who drew out of them their practical utility.

[40] James Clerk Maxwell, *A Treatise on Electricity and Magnetism*, (Clarendon Press, Oxford, 1873).

[41] See chapter ZZZZZ of this book[editors: reference here to the chapter on Maxwell and E&M] and also Bruce J. Hunt op. cit. ref. 39. for examples of aspects of electromagnetic waves such as reflection, refraction and energy propagation not treated by Maxwell himself.

[42] C. W. F. Everitt, *James Clerk Maxwell: Physicist and Natural Philosopher*, Charles Scribner & Sons, New York, 1975.

[43] Elizabeth Garber, Stephen G. Brush and C. W. F. Everitt (eds.) *Maxwell on Molecules and Gases*, MIT Press, Cambridge, Mass., 1986; Elizabeth Garber, Stephen G. Brush and C. W. F.

Everitt (eds.) *Maxwell on Heat and Statistical Mechanics*, Associated University Presses, New Jersey, 1995.

[44] W. J. Macquorn Rankine "Principle of the Equilibrium of Polyhedral Frames" p564 in *Miscellaneous Scientific Papers* (Charles Griffin & Co., London, 1881)

[45] Background on the Keith Prize courtesy of the Royal Society of Edinburgh.

[46] Edward John Routh, *A Treatise on Analytical Statics with Numerous Examples*, Chpt. 8, pp 229-251, (CUP, 2nd ed'n 1896).

[47] P. M. Harman, SLP2, reproduces four reports during his King's College years and over two dozen subsequent reports.

[48] In every year from 1864 to 1879 inclusive, except 1867, Maxwell was a co-author of one or more reports to the British Association for the Advancement of Science by various committees. He was on eight committees in total, half of which were concerned with electrical issues and half with other issues.

[49] King's College Council records, op. cit. ref. 7, p305. The rate for each matriculated student, which was essentially the salary, was advertised for Maxwell's successor as 4 guineas, in comparison with Maxwell's 5 gns.

[50] The Thames was at times like an open sewer and the 'great stink' of 1858 would have been remembered by many. Poor sewerage was a contributor to infectious diseases, the cause of 20% of London's deaths in the 1860s as detailed in the Encyclopaedia Britannica, op. cit. ref. 1, pp 827-828. In addition, coal smoke and city smog were responsible for the 'black wreath' – Wordsworth's phrase – of pungent and irritating poor air that contributed to respiratory diseases.

[51] Jordi Cat *Glenlair: a brief architectural history*, http://www.glenlair.org.uk/glenlair_history.asp on 6th October 2011.