Clerk Maxwell's Life and Work

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Clerk-Maxwell : his life and work

(Talk given at JCMB for a party of visiting Dutch schoolteachers)

0.1 The Clerks

James Clerk Maxwell was born in 1831, at No. 14 India Street in Edinburgh. India Street is a handsome street of terraced houses running down the slope north of Princes Street towards the estuary of the River Forth. The house today looks very much as it must have done when it was built, in 1820, for Mr John Clerk Maxwell, a not very enthusiastic Edinburgh lawyer. Mr Clerk Maxwell was a descendant of the Clerks of Penicuick; Penicuick is a village about 8 miles south of where we are today, and the Clerks had and still have an estate a couple of miles from the village. They were a family of some note in the intellectual life of Scotland. The second Sir John Clerk of Penicuick (1676-1755) was a painter, a very fine musician, and a friend of Correlli. (Some of his music is still available on CD.) He regretfully gave up music for politics around 1725. His youngest son, John Clerk of Eldin (1728-1812) was a famous engraver; also, he invented the tactics with which Admiral Lord Nelson won the Battle of Trafalgar in 1805 – in conditions of wind and weather for which those tactics were not intended ! In the 18th century, as the result of a marriage between a Clerk and a member of the much grander Maxwell family, an estate at Middlebie in the south-west of Scotland came into the possession of the Clerks, but with a condition that the holder of the estate must not hold a Clerk property, and must be called Maxwell.

0.2 Childhood years

When John Clerk Maxwell married in 1829 his wife encouraged him to build a house on his Middlebie estate, which he did, and he named the house Glenlair. James was born on 13-JUL-1831; soon afterwards he and his parents went down to Glenlair which for his first ten years was James's permanent home. He grew up a very intelligent boy with a lively curiosity and an astonishing memory, and until he was 8 years old he was educated by his parents. His father was an intelligent man, keenly interested in things mechanical, an enthusiastic amateur geologist, and fascinated by astronomy. He taught James about these things, and many others, on long walks in the country, from which they often returned with James's pocket stuffed with all manner of curious things; his mother, with a more orderly mind than her husband, contributed to James's education in other matters – such as reading and writing. But she died in 1839. After much thought about how James was to be educated without his mother's input, John Clerk Maxwell appointed a tutor to come and live in the house and see to the boy's formal instruction. From the outset James and his tutor detested one another. The tutor, who should never have been put in charge of such an intelligent boy, bullied him mercilessly in the classroom, and James took his revenge outside it. James's indifferent progress was attributed by the tutor to lack of ability and application, and it was two years before father John – alerted by his late wife's sister who was a frequent visitor to Glenlair – realised what was happening. The tutor was dismissed, and again John had to decide what to do about his son's education. It was decided that James should go to

Edinburgh to live with his father's widowed sister, aunt Isabella Wedderburn, and her numerous family, so that he could attend the Edinburgh Academy, a newish and up-market Edinburgh school. The Wedderburns lived just 'uphill and first left' from James's birthplace, in the very stately Heriot Row; they were an intelligent and lively family, and James's intense curiosity about anything and everything would thrive there. Meanwhile his father would visit Edinburgh frequently and spend time with his son.

0.3 Edinburgh Academy

At the time of his entry to Edinburgh Academy, James had discovered for himself and made models of four of the five Platonic solids, the regular polyhedra -– quite a feat for a 10-year old. But to his new classmates at the Academy, he was just an uncouth lad from the country, with a broad country accent, and prone to stammer, particularly when under pressure. Unlike his city-bred classmates he was dressed in clothes suited to winters in Glenlair including jackets and shoes designed and made by his father. The other boys derided James's 'oddities', nicknamed him "Daftie", and were with one or two rare exceptions blind to his good qualities. The didactic system at the Academy at that time has been described by Ivan Tolstoy as "institutionalised intellectual violence" (800 Greek irregular verbs had to be memorised by age 12 !), and Maxwell's mind was developed during this period not by the school but by the Wedderburn household. In that lively, questioning, stimulating company he found a happy and congenial home environment. Their experiments with hot-air balloons were recorded in skilful drawings by Jemima Wedderburn, 8 years older than James, who was to develop into a brilliant illustrator and famous water colourist. We see them trying out modest sized hot-air balloons in the stair-well of 31 Heriot Row, with James observing progress from part way up the stairs. Later we see them with much larger balloons in the open air, rushing after them as they escaped. James's father came up to Edinburgh frequently, and when James was 12 years old his father took him to a meeting of the Royal Society of Edinburgh, of which he was a Fellow, and in whose *Transactions* he had published a paper on a printing machine with automatic feed. He and James were to become fairly regular attenders at the R S E. At the age of 13 James began to study geometry formally, under the tutelage of a remarkable teacher, Mr Gloag. Maxwell blossomed, and his work improved in all his subjects. Two years later – still a schoolboy – he wrote a paper on *Oval Curves*, which was communicated to the Royal Society by Professor J D Forbes of this Department and was published in the *Transactions* of the R S E for 1846. In this paper the theory of the ellipse was generalised in a completely original way. From this time Forbes became a good friend of James and his father, and his influence at certain points in James's life was vitally important.

0.4 Edinburgh University

In 1847 – aged 16 – James left the Academy with prizes and medals acknowledging his academic merit, and proceeded to Edinburgh University where over the next three years he studied Logic and Metaphysics, Natural Philosophy (physics), Mathematics, and some Chemistry. While a student in Edinburgh James published two more papers through the Royal Society of Edinburgh;

one was a clever piece of geometry, the other was a piece of real, good quality physics, entitled *On The Equilibrium of Elastic Solids*. In it, an axiomatic reformulation of the field equations of elasticity which had been derived a little earlier by Stokes was given, and they were applied to a number of problems in elasticity. The results were verified experimentally, using the phenomenon of photoelasticity – discovered a good many years earlier by Brewster – to reveal the stress field in the material. This was a thoroughly professional piece of work on a topic of current interest, and it marked a significant development in the author. It's worth remembering, at this point, that James Clerk Maxwell, whom we usually think of as a theoretical physicist, had been an experimentalist since childhood. Wherever he was staying he had a laboratory with quite a lot of experimental equipment, some of which he made himself. He was much concerned about experimental precision, as we shall see later. He completed his studies in Edinburgh in the year the elasticity paper was published. Once again his father had to decide "What next?" He felt that James should now follow famiy tradition and become a lawyer. It took a lot of urging from friends, including a special visit from J D Forbes, to dissuade him from this, and to get him to agree to send James to Cambridge to continue his scientific education.

0.5 Cambridge

Maxwell went to Cambridge in 1850, aged 19. For four years he was an undergraduate, ending up as second wrangler (i.e. second in the mathematics final examination) and first equal Smith's prizeman. He stayed on in Trinity College where he became a Fellow in 1855, and he left Cambridge in 1856 to go to Aberdeen as Professor of Natural Philosophy in Marischal College. C W Everitt, one of Maxwell's biographers, remarks that "It was Maxwell's habit to work on different subjects in sequence, sometimes with an interval of several years between successive papers on the same subject." For this reason it is difficult and confusing to try to follow the development of his work in a strictly chronological framework, so I shall put on the screen a chronological outline of his career as a background, while I talk about his work topic by topic.

0.6 Fields of research

The main topics of James Clerk Maxwell's work in physics were:

- Geometrical optics
- Colour perception and measurement, colour photography
- Saturn's rings
- The theory of servomechanisms
- Stresses in engineering structures
- Relaxation processes
- Electromagnetism
- Kinetic theory and statistical mechanics.

See also lists of significant dates, and research topics (below0.13)

0.6.1 Geometrical optics

Maxwell's work on geometrical optics led to two papers. The first described the 'Maxwell fish-eye lens', which gives a perfect point image of any point source wherever in space it may be. The second paper established *Maxwell's theorem for an absolute instrument*, which defines those geometrical transformations between finite objects and images which can be produced by perfect imaging systems – where such exist!

0.6.2 Colour

While a student in Edinburgh, Maxwell had been encouraged by Professor Forbes to work in the professor's own laboratory. This he did, often for very long hours. Sometimes he would work on topics suggested by Forbes, sometimes on problems of his own. One topic which interested them both at that time was colour vision, which Thomas Young had interpreted around 1800 in terms of three primary colours and three sets of colour-sensitive receptors in the eye. Brewster had considerably confused the issue in the 1830's, and effectively prevented widespread acceptance of Young's ideas. Forbes and Maxwell correctly identified the three primary colours as R, G and B, and established quantitative equations to determine colours formed by combinations of the three primaries. In 1854, after his graduation in Cambridge Maxwell resumed this work. He showed that the effects of colour blindness could be simulated by forming mixtures of only two primaries. He designed a colour triangle on which all these phenomena could be displayed quantitatively in a geometrical way. He invented a 'colour box' which enabled him to position three slits at any three points in the spectrum of white light, and then recombine these pure spectral colours with any desired relative intensities. With this instrument he was able to determine the co-ordinates of the spectral locus on his geometrical display for any observer; with his wife as observer (in Aberdeen in 1858-60) he obtained results which are comparable with the best modern work. Maxwell's work on colour measurement established the modern, industrially important, science of colorimetry; people working in the field today are using 'colour boxes' which are quite clearly developments from Maxwell's 1858 apparatus. In 1861 Maxwell displayed to the London Royal Society the first colour photograph, formed by making three 'colour-separation negatives' of a tartan ribbon, producing three positive transparencies from them, and projecting in superposition each positive through the filter used to make its negative. It was not realised at that time that the emulsions he used had no red sensitivity, so the negative he formed through his red filter could not be what he thought. However, a curious combination of coincidences enabled him to produce a quite good and apparently full colour image of the ribbon. The correct explanation of what had happened was given after a very beautiful piece of research at the Eastman Kodak laboratories in 1960.

0.6.3 Saturn's rings

A problem which had bothered astronomers since the previous century was that of Saturn's rings – what was their structure, and why was it stable? Laplace had shown that a solid ring would not be stable, and had conjectured that the rings might consist of an enormous number of irregular chunks of solid materials. That was how things remained for 75 years, until in 1855 the problem of Saturn's rings was set as the topic of the Adams prize at Cambridge. (The Adams prize was named in honour of the Cambridge astronomer John Couch Adams). Maxwell worked on the Saturn's Rings problem over a period of four years. He showed that, of the structures that had been or could be suggested, only Laplace's cloud of solid fragments was a possible stable structure, and he showed that slow changes in the dimensions of the rings, such as had been noticed in the previous 75 or 80 years, were to be expected. He analysed by means of Fourier's Series the conditions of stability of such systems, in what Sir George Airy, the Astronomer Royal, called "one of the most remarkable applications of mathematics to physics that I have ever seen". It was this knowledge and mastery of the available mathematical tools that was the principal benefit Maxwell acquired in Cambridge.

0.7 Appointment to Aberdeen

During those four years Maxwell had given up his Trinity College Fellowship to go to Aberdeen, as Professor of Natural Philosophy at Marischal College, one of two university-level colleges in Aberdeen at that time. Probably his chief reason for this move was that his father was very ill in late 1855 and early 1856, and Maxwell felt that in Scotland he would be better able to help with the care and supervision of the Glenlair estate. The academic year at Aberdeen ran from November to April, so that James could spend half the year at Glenlair, and half in Aberdeen. In fact, John Clerk Maxwell died after his son had applied for the Aberdeen chair, but before the appointment was made, so that James became entirely responsible for the country estate. In Aberdeen he continued his work on colour, and on Saturn's rings, and followed up a paper On Faraday's Lines of Force (1855-56) which was his first step on the way to the greatTreatise of the 1870's. The years in Aberdeen were significant for Maxwell personally – after his father's death he matured considerably, and in 1858 he married Katherine Mary Dewar, daughter of the Principal of Marischal College. Very little is known about her. She was to help her husband very substantially in his experimental work on colorimetry, and in his great experiments on the viscosity of gases; she was apparently not a very sociable person, possibly rather neurotic, and since Maxwell himself was an intensely private person little about her emerges from his correspondence with his friends.

0.7.1 Kinetic theory → Statistical mechanics

Maxwell had been thinking for some time about the structure of gases. In a remarkable paper read at the British Association meeting in Aberdeen in 1859 and published in 1860 with the title *Illustrations of the dynamical theory of gases*, he developed Clausius's idea of equipartition of energy between different modes of behaviour of many-particle systems, explained the results of Graham's experimental work on diffusion, established the utility of the idea of the mean free path, gave the statistical formula for the velocity distribution of the molecules in a gas, explained the mechanism of what are called 'transport processes', and made the startling prediction that the viscosity of a gas should be independent of its pressure. This prediction he subsequently confirmed in a series of beautiful experiments carried out with the help of his wife in London between 1863 and 1866. With this Aberdeen paper statistical methods came into physics to stay, wherever very complex systems of many particles had to be considered. In 1867 there followed another paper On the dynamical theory of gases in which the kinetic-molecular theory was shown to account for most of the known properties of gases, and was given a secure foundation. The idea of relaxation processes and relaxation times was introduced and related to such phenomena as viscosity and heat conduction. This was a truly great paper – Boltzmann enthusiastically compared it to a great symphonic poem – and it was surpassed only by Maxwell's 1878 paper *On Boltzmann's theorem on the average distribution of energy in a system of material points.* This paper, along with related papers by Boltzmann, established statistical mechanics as a mature discipline in its own right.

0.8 From Aberdeen to London

When Aberdeen had fused its two Colleges into one University in 1860 the senior of the two Nat Phil professors – a man called David Thomson – was retained, and Maxwell had to go. He had already applied for the Edinburgh chair which was vacant, but it went to his former companion at Edinburgh Academy and Cambridge, P G Tait; Maxwell then applied for the vacant chair at King's College London, and was appointed there. For the next six very productive years the Maxwells divided their time between Glenlair and London – where Maxwell met and became a friend of Michael Faraday.

0.8.1 Electromagnetism

In his inaugural address at King's College Maxwell said that "In the electrical and magnetic sciences . . . an immense mass of facts has been collected, and these have been reduced to order and expressed as the results of a number of experimental laws, but the form under which these laws are ultimately to appear as deduced from general principles is as yet uncertain". In 1861-2 he published a paper *On physical lines of force* in which he introduced the famous vortices to simulate the properties Faraday had attributed to the lines of magnetic force – namely, that lines of force tend to contract and find the shortest route between their terminations, subject to the constraint that neighbouring lines of force tend to repel one another. From this he proceeded to develop a model which was so successful that in 1864, in *A dynamical theory of the electromagnetic field* (pub.1865) he was able to announce that :

> We have reason to conclude that light itself (including radiant heat and other radiations, if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws

and he pointed out that the speed of light was equal to the ratio of the electrostatic to the electromagnetic unit of charge. What an advance, in the four years following the inaugural lecture! This paper, by the way, introduced the vector functions curl, grad, and div.

0.8.2 Electrical and magnetic units → Governors

Meantime in 1861 the British Association had set up a committee under the chairmanship of William Thomson to establish a system of internationally acceptable electrical and magnetic units. This produced a number of papers on the relationships between these units, including one by Maxwell and his one-time classmate at Edinburgh Academy, Fleeming Jenkins, who was Professor of Engineering in Edinburgh. Their work on Thomson's committee led to their collaboration on a method for the establishment of the ohm. The experimental procedure they arrived at involved the rotation of a small coil with constant angular velocity in a uniform magnetic field from a pair of Helmholtz coils. Maxwell remembered that the James Watt steam engines had a centrifugal speed governor to stabilize their operation, and he developed the theory of such governors and so initiated the theory of feedback and automatic control, and became in fact the father – or possibly grandfather – of cybernetics. Around this time Maxwell also refined the technique of *Dimensional Analysis*, and introduced the notation we still use. The system of units proposed by Thomson's committee was adopted in, I think, 1881 as the electrical international system of units. In a short and extremely important *Note on the electromagnetic theory of light* published in 1868 (the same year as his paper *On governors*) Maxwell published the equations governing the propagation of electromagnetic waves, based on four well attested experimental laws. The equations were given in integral form, as they were to appear five years later in the Treatise on Electricity and Magnetism.

0.9 Return to Glenlair

Maxwell had left King's College in 1865 – he was a poor lecturer and an ineffective disciplinarian, and he hadn't enjoyed the heavier teaching load and longer teaching year than he had had in Aberdeen. He didn't need the money, he felt that he would have more time for – to quote himself – "experiments and speculations of a physical kind, which I could not undertake as long as I had public duties". He also had time to attend to the estate and to his tenants, and to the realisation of a dream his father had cherished, and which he himself had inherited. His father had designed Glenlair house as a modest laird's house some thirty-five or so years earlier. At the time of his death John Clerk Maxwell had sketched an enlargement of the house – rather hideous really – and James set about getting it built. Very sensibly he and Katherine went off to mainland Europe in 1867 while the building was going on. During this journey, Tolstoy reports, "Maxwell, who had a gift for languages, became fluent in Italian and improved his French and German although, for some reason, he had difficulty with Dutch." !

0.10 The Cavendish Laboratory

The next four years at Glenlair were fairly peaceful and useful. The Maxwells still had a house in London, where they went for part of each winter; James was working at the Treatise and on his developing ideas about the theory of gases, he was still involved with the British Association committee on the electrical and magnetic units, and he was engaged in a fair amount of correspondence with people interested in his work on colour. His wife seems to have enjoyed the country life, and they did some entertaining of visitors and neighbours. Then, in 1871, came the invitation to return to Cambridge to set up and direct the proposed Cavendish Laboratory of experimental physics. James was as interested as ever in experimentation, and he saw this as a wonderful opportunity. In passing, perhaps it should be said that he was not the first choice for the job – William Thomson, Lord Kelvin was the first to be approached and to turn it down, and Helmholtz was the second. But the job of Director of the as yet non-existent laboratory, and the new Chair of Experimental Physics that came with it, was accepted by Maxwell – after some persuasion by, among others, Stokes and Lord Rayleigh. Maxwell embarked on a round of visits to already existing laboratories, and then went to Cambridge to plan with the architect, and oversee the building and the equipping of the laboratory. From the outset he was determined that precision and sensitivity were to be the hallmark of the laboratory's work, and so it came about. Among the first of Maxwell's experiments in the new laboratory was his demonstration in 1873 that an aqueous solution of Canada balsam when stressed shows short-term double refraction with a relaxation time of about 10^{-2} sec; Brewster had discovered double refraction in strained solids about fifty years before, and Maxwell now concluded that materials exhibit the features of solids in times less than the stress relaxation time, and of liquids over longer times. Maxwell continued to work energetically at a great variety of tasks, theoretical, experimental, editorial and administrative; his last original scientific paper, published in 1879, was a major one, *On stress in rarefied gases arising from inequalities of temperature.* This and earlier papers in that field continued to provide challenges to experimenters right into the 1950's.

0.11 Illness and death

In 1877 Maxwell's health began to decline, and at times in 1878 and 1879 he was unable to work because of pain. Early in October 1879 he was told that he had no more than a month to live, and he died on November 5th.

0.12 Retrospect

Einstein was to remark that Maxwell's greatest achievement was his revolutionary introduction of mathematics into physics. This is an interesting remark. Obviously physicists long before Maxwell had used mathematics in physics, so that isn't what Einstein was referring to. But consider for a moment how Maxwell proceeded from the mathematical description of a model of the electric and magnetic fields in space in terms of vortices separated by roller bearings, to the supreme abstraction of the *Treatise* – stripping away in stages the imagery of the model until finally all that remained was the mathematics – so that the mathematics became the model. This was the great achievement, the great liberation which transformed physics and made possible the development of the two great ideas on which twentieth century physics is built – the relativity idea which was the culmination of classical physics, and the quantum idea which is the essence of modern physics.

Richard M Sillitto 24/08/93

0.13 Successive periods in Maxwell's life

- Glenlair, 1831-41
- Edinburgh Academy, 1841-47
- Edinburgh University, 1847-50
- Cambridge University, 1850-54-55-56
- Aberdeen University, 1856-60
- King's College, London, 1860-65
- Glenlair, 1865-71
- Cavendish Laboratory, 1871-79

0.14 Principal research topics

- Geometry (Oval Curves 1845, Rolling curves , 1848)
- Elasticity and photoelasticity (1849-50)
- Maxwell's Top (1857)
- Saturn's rings (1855-59)
- Optics (Fish-eye lens 1854, M's Theorem for absolute instruments 1858)
- Colour (Perception 1855, Colorimetry, Colour Photography 1861)
- Stresses in bridge structures etc (1864)
- Electromagnetism
  (Re-interpretation of Faraday 1855-61, writing of the Treatise 1865-71, the Treatise published 1873)
- Statistical Mechanics (Kinetic theory, Viscosity etc 1860, General theory 1866,-67,-76,-78,-79)