James Clerk Maxwell : his qualities of mind and personality as judged by his contemporaries

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It is unbelievable
How simple and straightforward
Each result appears
Once it has been found
And how difficult,
As long as the way which leads to it is unknown

[Ludwig Boltzmann 1894]

James Maxwell Clerk as undergraduate at Trinity College holding Colour Top

Introduction

Trustees of the James Clerk Maxwell Foundation, finding themselves from time to time escorting visitors round the birthplace and former Edinburgh home (14 India Street, Edinburgh) of James Clerk Maxwell are often asked about the special qualities of mind which made Maxwell so outstanding in his field. While it is difficult to do justice to so grand a theme it seems worthwhile to attempt the task at the suggestion of the late Professor Drazin, the former Editor of 'Mathematics Today', who sadly died very recently. It is hoped that this article will add to the appreciations of Maxwell by previous writers, particularly Professor C. W. F. Everitt[i]

Although Maxwell's distinguished scientific peers like Professor P.G. Tait[1], Sir J.J. Thomson[2], and Sir Ambrose Fleming[3] had no reservations about applying the word 'genius' to Maxwell, that word alone, without

[1]Peter Guthrie Tait (1831-1901), FRSE, Senior Wrangler and 1st Smith's Prizeman, 1852, Professor of Natural Philosophy, University of Edinburgh, 1860-1901. Scientific colleague of Maxwell's from the time they were schoolboys at the Edinburgh Academy. It remains a mystery to this day why Tait never became an FRS given his close friendship with Maxwell and with Lord Kelvin who became the President of the Royal Society.

[2] Sir J J Thomson (1856-1940), FRS, Nobel Prize for Physics 1906 for the discovery of the electron.

further analysis, reveals little as to the distinguishing qualities of mind which they had noticed so singularly developed in Maxwell.

The scientist and Cambridge mathematical coach William Hopkins[4], showed great perception in assessing the qualities of his students. In addition to Maxwell, Hopkins had taught Kelvin, Stokes, Cayley, Tait, Routh and Todhunter and is authoritatively reported to have said about Maxwell,

> *…he is unquestionably the most extraordinary man I have met with, in the whole range of my experience; it appears impossible for Maxwell to think incorrectly on physical subjects but in his analysis he is far more deficient….*[ii]*.*

In his testimonial for Maxwell's application for the professorship of Natural Philosophy at Aberdeen, Hopkins wrote words of uncanny prescience:-

> *During the last 30 years I have been intimately acquainted with every man of mathematical distinction who has proceeded from the University, and I do not hesitate to assert that I have known no one who, at Mr. Maxwell's age, has possessed the same amount of accurate knowledge in the higher departments of physical science as himself… His mind is devoted to the prosecution of scientific studies, and it is impossible that he should not become (if his life is spared) one of the most distinguished men of science in this or any other country*[iii]*.*

Professor Tait , a lifelong scientific colleague of his stemming from the days when they had been pupils together at the Edinburgh Academy, said that Maxwell had arrived in Cambridge:-

> *…with a mass of knowledge which was really immense for so young a man, but in a state of disorder appalling to his methodical private tutor …William Hopkins*[iv]*.*

Hopkins' statements reveal that Maxwell was dedicated to scientific studies and by the time he was a university student had amassed a vast repertoire of accurate knowledge in the physical sciences. One

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[3] Sir Ambrose Fleming (1849-1945), FRS, Professor of Electrical Technology at University College, London. Student of Maxwell at the Cavendish Laboratory. Inventor of the thermionic valve. Died age 95, his career having spanned the period from Maxwell to television.

[4] William Hopkins, M.A., F.R.S., 7th Wrangler 1827, distinguished geologist, President of the Geological Society 1851-53, President of the Mathematics and Physics Section of the British Association for Advancement of Science 1849 and President of the Geology Section 1851 and 1858. Published papers on geology. Seems to have made his living, perhaps rather surprisingly for such a distinguished man, as a Cambridge coach although coaches could apparently earn more than professors. Because of his reputation as a coach, he coached the ablest students in Cambridge.

of Maxwell's outstanding qualities was his superb physical intuition but he did not display the same degree of skill at mathematical analysis.

Peter Guthrie Tait

Maxwell possessed an outstanding intellect. He was described by P.G. Tait as possessing:-

.... one of the most piecing intellects of modern times[v].

The distinguished American physicist, Professor Henry Rowland[5] wrote a letter during his 1875 visit to the United Kingdom:-

> *As to the professors, they are all men like the rest of us! After seeing Maxwell I felt somewhat discouraged for here I met with a mind whose superiority was almost oppressive but I have since recovered and I believe I see more clearly the path in which I hope to excel in the future. It is midway between the purely mathematical physicist and the purely experimental and in a place where few are working. Maxwell is a better mathematician than I shall ever become, but then I think I may become at least equal as an experimentalist.* [vi]

It was not in Maxwell's character to use his intellect as a weapon of superiority, particularly against someone like Professor Rowland for whom Maxwell had the highest regard and who became a good friend. Rowland had witnessed at close quarters the knowledge, speed of thought and imagination of Maxwell and, like all who met him, was greatly impressed. He realised that he could never match Maxwell as a theorist but could match him as an experimentalist, and subsequently may have surpassed him as such. For American readers it may be interesting to note that Maxwell also championed the work of Professor Willard Gibbs[6]. Through his promotion of Rowland and Gibbs, Maxwell was a strong supporter of physics in the New World.

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[5] Henry Augustus Rowland (1848-1901), FRS, Professor of Physics at John Hopkins University, Member of the National Academy of Sciences, First President of the American Physical Society, Vice-President of the American Association for the Advancement of Science (1883).

[6] Willard Gibbs (1839-1903), Professor of Mathematical Physics at Yale University. Maxwell once wrote to Tait, 'Read Prof. J Willard Gibbs, on the Surface whose co-ordinates are Volume, Entropy and Energy' and added with his characteristically pawky sense of humour, knowing his friend to be more than something of a chauvinist, 'He has more sense than any German'.

Love of the subject and research/investigative ability

Lewis Campbell[7] said in his biography of Maxwell (Campbell and Garnett[8] biography of 1882, referred to as the C.&G. biography[vii]):-

> *He never sought fame, but with sacred devotion continued in mature life the labours which had been his spontaneous delight in childhood.*

It is very clear from the C.&G. biography that from early boyhood Maxwell had a deep love of the investigation of the workings of Nature. As a small boy he was always asking, in the Gallowegian accent and idiom, *"What's the go o' that?"* and on receiving an unsatisfactory answer asking *"but what's the particular go o' that"*. As he embarked on a career he never doubted what would be his chosen path.

Lewis Campbell

When not asking questions, he was engaged in *doing* and *making* and Campbell and Garnett say:-

> *..whenever he saw anything that demanded constructive ingenuity in the performance, that henceforth took his fancy, and he must work at it. And in the doing it, it was ten to one but he must give it some new and unexpected turn and enliven it with some quirk of fancy.*

The investigative as well as the creative side of Maxwell's mind had been laid down very early.

Maxwell's school progress at the Edinburgh Academy, at which he enrolled at age 10, had a slow start and at age 12 he was placed 19th in the class. However by the time he left the Academy at age 16 he had risen to 2nd place. The standard of pupils in Maxwell's class was high. Fellow pupil Lewis Campbell was Dux (first academically), but the pupil with the outstanding school record was Peter Guthrie Tait who was in the class below Maxwell and was dux of every year during his school career. It was predicted, even while at school, that Tait would be a future Cambridge Senior Wrangler, a prediction which was fulfilled in 1852 when, at the age of 20, Tait became one of the youngest, perhaps the youngest, Senior Wrangler on record.

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[7] Professor Lewis Campbell (1830-1908). Maxwell's biographer. Blackstone Medallist at Glasgow University, Snell Exhibitioner at Balliol, Oxford, First Class Honours in Greats, Fellow of Queen's College, Oxford and Professor of Greek at St Andrews University. Dux of the Edinburgh Academy in Maxwell's year and school friend of Maxwell.

[8] William Garnett (1850-1932), 5th Wrangler 1873, was Maxwell's first Demonstrator at the Cavendish Laboratory where he worked from 1874-80. Professor of Physics, University College, Nottingham. Principal of Durham College of Science, Newcastle-upon-Tyne.

However, writing later about their school days in the 'Chronicles of the Cumming Club', Tait said of Maxwell, simply:

> *It was in those days that some of the early developments of genius showed themselves……*

In the 1947 Edition of the Encyclopædia Britannica is the entry about Maxwell which was written by Tait. In it he says:

> *The first paper of Maxwell's in which an attempt at an admissible physical theory of electromagnetism was made was communicated to the Royal Society in 1864. But the theory in fully developed form first appeared in 1873 in his great treatise of Electricity and Magnetism. This work was one of the most splendid monuments ever raised by the genius of a single individual.*

Maxwell's school record belies his ability. It suggests that Maxwell never paid a great amount of attention to a narrow focus on schoolwork. It would seem that during his formulative years he read extensively and pursued his own studies and investigations far beyond the school syllabus[9]. Even at Cambridge fellow students shook their heads in disbelief at Maxwell's discursive reading, "which would never pay in the Tripos".

It was outside formal school activities that Maxwell's ability first showed itself. His own extra mural researches and investigations culminated in the production at age 14 of a paper *On the Description of Oval Curves, and those having Plurality of Foci.* In this he demonstrated a way of his own invention of drawing Cartesian Ovals with pins and string and, using geometry to investigate their properties, showed that his Ovals and those of Descartes were the same.

It seems likely that, consciously or sub-consciously, Maxwell began to recognise at that time that he had the ability to make original investigations and work out new ideas for himself something that must have given him a great intellectual thrill. There may be a lesson here for to-days education system which with its pressure on schoolwork and narrow concentration on examinations may regrettably fail to give to-day's pupils the early opportunity to discover that they have a capacity to find out things for themselves and to make original investigations.

Maxwell was fortunate that his interest in scientific matters was fostered by his father and his uncle, John Cay, both Fellows of the Royal Society of Edinburgh. They took the young Maxwell to meetings of that Society. At age 15, Maxwell and Lewis Campbell were taken by John Cay to see the private

[9] During the school term Maxwell lived with his widowed aunt, Isabella Wedderburn (née Clerk) and cousins in one of the finest Georgian houses in Edinburgh's New Town at 31 Heriot Row. Isabella's late husband, James Wedderburn, was, at the time of his death, the Solicitor General for Scotland and had an extensive library. Clerk Maxwell's father, being himself a widower, acted as father to his sister's children as his sister acted as mother to James. Jemima, the daughter of Isabella and Maxwell's cousin, was a prolific artist and one of the finest portrayers of animals of the Victorian era.

scientific laboratory of William Nicol[10], inventor of the Nicol polarising prism. Following this visit, Nicol presented Maxwell with two of his prisms, which became treasured possessions of the latter. Maxwell was later to describe this visit as the turning point of his life: from that visit onwards he apparently knew that the pursuit of scientific investigations was to be his career. Within a few years Maxwell had produced two further papers for the Royal Society of Edinburgh, *On the Theory of Rolling Curves* (presented at age 17) and *On the Equilibrium of Elastic Solids* (presented at age 18). Maxwell was also very grateful for the support which he received from James D. Forbes, FRS, Professor of Natural Philosophy at Edinburgh University and later Principal of St Andrews University.

Fertility of imagination and creative ability to initiate wholly new ideas

Maxwell had an extremely fertile imagination, flowing with ideas, which he found very difficulty to gear down to the level of the students. In his obituary tribute to Maxwell, P.G. Tait wrote:-

> *His books and his written addresses (always gone over twice in manuscript) are models of clear and precise exposition; but his extempore lectures exhibited, in a manner most aggravating to the listener, the extraordinary fertility of his imagination.*[viii]

At Aberdeen his lectures were described by one of his most able students, David Gill (later Sir David Gill)[11] as follows:-

> *He would begin reading from manuscript then he would stop remarking "perhaps I might explain this". Then he would run off after some idea that had flashed on his mind thinking aloud as he covered the blackboard with figures and symbols, generally outrunning the comprehension of the best of us. Then he would return to his manuscript but by this time the lecture time had nearly run out. To those who could catch a few sparks that flashed as he thought aloud at the blackboard in lectures, or when he twinkled with wit and suggestion in after-lecture conversation, Maxwell was supreme as an inspiration.*[ix]

In 1908, in an after-dinner speech in London to the Aberdeen University Club, Gill reminisced in a rather light-hearted vein about his Aberdeen days:-

[10] William Nicol (1768-1851) , Edinburgh geologist and paleontologist, inventor of the Nicol prism which, after its invention, became the most convenient way of producing polarised light. Invented a technique for preparing transparent slivers of rocks and crystals whose potential was not recognised for 40 years until 1853.

[11] Sir David Gill, KCB, FRAS, Hon. FRSE, FRS, Director of the Observatory at the Cape of Good Hope and one of the 19th century's most distinguished astronomers. President of the British Association for the Advancement of Science, 1907. Maxwell in a testimonial for Gill said " Mr. David Gill was one of my ablest students in Marischal College".

Then there was another man of whom I would like to say something, a man whose memory sticks to me in a thousand ways – and a man of whom I had a tremendous idea – that was Clerk Maxwell. He was one of two or three of the greatest geniuses who have ever lived since the days of Newton and yet they did not understand him in Aberdeen somehow. He was not a schoolmaster. His lectures were terrible and his experiments always failed – but they were always much more interesting in the failure than if they had gone on. Those of us who chose to stay behind after class used to get a most delightful hour or two and learn an immense deal we never forgot – a great deal we did not understand at the time, but that came back to us afterwards – until Mrs. Clerk Maxwell arrived wondering why the Professor did not come home to his dinner and carried him away nolens volens.[x]

The flow of Maxwell's ideas was not confined merely to scientific subjects. His biographer, Lewis Campbell, wrote:-

…no-one ever conversed with him (Maxwell) for five minutes without having some perfectly new ideas set before him; sometimes so startling as to utterly confound the listener, but always such as to well repay a thoughtful examination.

Maxwell's skill in versification[12] was a further example of his creative side. Few men were ever able to hide the deepest irony so subtly under a veil of apparent innocence as Maxwell did in his poetry. The charm on the surface often concealed a quite contrary meaning for those able to see beneath.

Maxwell's lectures were always humorous (usually ironically so) and his mode of expression eloquent although not always clear. However, as Sir David Gill said, " to those who could catch a few of the sparks that flashed as he thought aloud …. or when he twinkled with wit and suggestion ….. Maxwell was supreme as an inspiration." Sir David Gill described his attendance at Maxwell's lectures as the turning point of his life as Maxwell had so described his visit to the laboratory of William Nicol.

All geniuses create by the application of imagination to knowledge. Maxwell had both in abundance. Gauss described Riemann as having a *"gloriously fertile imagination"*[13]. Such praise could equally apply to Maxwell.

As well his ability to initiate wholly new ideas like a statistical approach to the velocity of gas molecules or a vector analysis approach to the 'mathematisation' of Faraday's concept of fields, Maxwell had a very practical side. He exhibited great skill in designing mechanical devices to illustrate particular aspects of physics (his interest in mechanical devices is reminiscent of a corresponding interest exhibited by Sir Isaac Newton and John von Neumann). The colour top

[12] C. & G. contains some 40 poems by Maxwell.

[13] Gauss was referring, inter alia, to the Riemann's introduction of topological concepts into the theory of complex variables and his introduction of ideas which now form the basis of modern differential geometry.

demonstrated in a ingeniously simple way that three basic colours mixed together in the right way could be made to match any fourth colour i.e. the tri-chromatic theory of colour, and illustrated how colours are perceived by the human eye in distinction to how they arise in the electromagnetic spectrum which is based purely on frequency of vibration. Other ingenious devices were the dynamical top, the colour box, the model of Saturn's Rings, the zoetrope and the model of Gibbs' thermodynamic surface for water. Maxwell, as the first Cavendish Professor, had the finest instrument makers of the Victorian age construct with precision engineering, the mechanical devices for the new laboratory, many of which he had designed.

Physical intuition, which went together, as it often does, with a powerful geometrical imagination.

William Hopkins, as mentioned above, referred to the extraordinary physical intuition which Maxwell exhibited but commented on certain deficiencies in his mathematical analysis. Campbell and Garnett quote a fellow undergraduate of Maxwell's who commented as follows:-

> *Our lecturer had filled the blackboard three times with the investigation of some hard problem and was not at the end of it, when Maxwell came up with a question whether it would not come out geometrically, and showed how with a figure and in a few lines, there was the solution at once.*
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> *One striking characteristic was remarked on by contemporaries of Maxwell who with him attended Hopkins' lectures. Whenever the subject admitted of it, Maxwell had recourse to diagrams though the rest might solve the question more easily by a train of analysis.*

J.J. Thomson in *James Clerk Maxwell: A Commemorative Volume 1831-1931* [14] put it as follows:-

> *This is an example of his general method of thought which was to proceed step-by-step from one definite idea to another, until he had reached his goal, instead of getting there by means of symbols and equations without any visualisation of the intermediate steps.*

In this context it is interesting to recall the conversation between Paul Dirac[15] and Abdus Salam[16] as recounted by Abdus Salam:-

[14] Thomson J J. and other authors (1931), *James Clerk Maxwell: A Commemoration Volume (1831-1931)* Cambridge University Press.

[15] Professor Paul Dirac (1902-84), Nobel Prize for Physics in 1933 for work on anti-particles. The existence of the positron was predicted theoretically by Dirac in 1930 and found experimentally by Anderson in 1932.

[16] Professor Abdus Salam (1926-1996), Nobel Prize for Physics in 1979 for unified theory of weak and electromagnetic force. Thus he unified three forces of nature as Maxwell had unified two. Other forces are the strong nuclear force and gravitation. Maxwell had a look at trying to bring gravitation within the fold but realised the time was not ripe for progress in this direction.

Once Dirac asked me (i.e. Abdus Salam) whether I thought geometrically or algebraically. I said I did not know what he meant, and could he tell me himself how he thought. He said his thinking was geometrical. I was taken aback by this because Dirac, with his transformation theory, represented for my generation the algebraic movement in physics par excellence. So I said: "I still don't understand." He said, "I will ask you a question. How do you picture the de Sitter space?" I said, "I write down the metric and then think about the structure of the terms in the expression." He said, "Precisely as I thought. You think algebraically……I picture, without effort, the de Sitter space as a four-dimensional surface in a five dimensional space.[xi]

Sir Michael Atiyah, OM, FRS, in his Presidential Address to the Mathematical Association, *'What is Geometry'* said:-

…geometry is that part of mathematics in which visual thought is dominant whereas algebra is that part in which sequential thought is dominant…

Maxwell excelled in visual thought, thinking geometrically by wishing to 'see' things, rather than thinking sequentially, analytically or algebraically. It was said of Riemann, one of the most profound and imaginative mathematicians of all time that ...... *he never tried to conceal his thought in a thicket of formulas.*

Unusual degree of patient determination

From the letters written by Maxwell it is clear that he possessed a great capacity to concentrate on a problem for long periods. For example, in August 1857 he wrote in regard to his work on the Adams Prize for which the subject set in 1855 was 'The Motions of Saturn's Rings' , ..*"I have been battering away at Saturn's rings….* In November 1857 he wrote *"I am very busy with Saturn on top of my regular work..."* and in December, *"I am still at Saturn's rings."*

P.G. Tait said in his obituary tribute to Maxwell:-

There can be no doubt that in this habit of constructing a mental image of every problem lay one of the chief secrets of his wonderful success as an investigator. To this was added an extraordinary power of penetration and an altogether unusual amount of patient determination.

Maxwell's essay on Saturn's Rings appears to have been the only one submitted. One imagines that others attempted the problem and can only conclude that they did not have the necessary power of penetration or patient determination to carry the project through.

A Unique Family Tree.

On his father's side, Maxwell came from the Clerk's of Penicuik near Edinburgh and on his mother's side from the Cay's of Northumberland.

The Clerk family had, from time to time, thrown up men of such conspicuous talent that the word genius had been used about previous members of the family. Sir Walter Scott himself had praised the heritable genius of the Clerks.

Maxwell's uncle Sir George Clerk, DCL, FRSE, FRS was the President of the Zoological Society in the UK at the time at which Darwin's Theory of Evolution exploded on to the scientific scene.

Maxwell's first cousin, Major General Henry Clerk, FRS, was a member of the Council of the Royal Society of London and contributed a number of scientific papers to various learned journals including the Transactions of the Royal Society.

Sir John Clerk, FRS, FSA, Maxwell's great-great-grandfather - well known to those who have studied the cultural history of Scotland - was described in his day as the *'great genius of the North'* because of the vast range of his talents and interests and his leadership in cultural matters. As a mere example of a small part of his range of abilities it is worth mentioning that Sir John, although only professing to be an amateur musician, was, in fact, a highly accomplished harpsichordist who…*excelled to a fault,* and who as a composer, …*mastered the musical lingua franca of Europe with precocious competence*….[xii].

On his mother's side, the Cay's produced two high Wranglers[17] in the Cambridge Mathematical Tripos (apart from Clerk Maxwell) and a Straiton Gold Medallist[18] – the top award for mathematics- at Edinburgh University, as well as a distinguished judge and a sheriff who was interested in scientific matters and fond of calculation as a voluntary pursuit. It seems likely that Maxwell's mathematical talent came, in the main, from the Cay side of the family.

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[17] Henry Boult Cay, 2W 1752, barrister, a distant ancestor of Maxwell and Charles Hope Cay (1841-68), 6W 1864, Maxwell's cousin, Mathematics Master at Clifton College, Member of the Alpine Club who climbed the Jungfrau but died at age 27.

[18] William Dyce Cay M Inst CE, FRSSA, FRSE (1838-1925) Maxwell's cousin and best man at his wedding. He said, "His [Maxwell's] tuition and example had a good effect as I got the highest prizes in my Classes …….viz. Straiton Gold Medal ….". He was a distinguished engineer who won the Makdougall Brisbane Prize of the Royal Scottish Society of Arts for a paper 'Construction of Mine Works with Concrete Bags'. He had done his apprenticeship with James Thomson, the brother of Lord Kelvin.

Personal Qualities

It is a curious fact that, although Maxwell's written expositions were a model of clarity, his conversation (and almost certainly his lectures unless read verbatim from text) often seemed disjointed and difficult to follow since his speech could not keep up with the rapidity of his mind (which he could not control) and intermediate steps were often missed out.

H. M. Butler, later Master of Trinity College, Cambridge when Maxwell was Cavendish Professor and Fellow of Trinity is reported to have said, after he had gone for a walk with Maxwell, that Maxwell talked the whole time and although he (Butler) had not understood a word, he would not have missed the occasion for anything!

However, despite these apparent handicaps, there is no doubt that Maxwell liked conversation and was very happy to talk on a range of subjects outside the scientific field. For example, his knowledge of English literature and the scriptures was remarkable for both its extent and exactness.

The self-deprecating side of Maxwell's humour is illustrated by the letter he wrote to Lewis Campbell after he (Maxwell) had secured his Fellowship of Trinity in 1855 at his second attempt. He commented *....Bad mathematics do no man any harm (with examiners) but bad classics do. Thompson* [Regius Professor of Greek] *said before I went in* [i.e. went in for the Trinity Fellowship] *that if they elected me they had never let through such bad classics*!

In 1868 the Principal-ship of St Andrews University became vacant on the retirement of Professor James Forbes and it appears that Maxwell applied, although he had some reservations in doing so. He finally concluded that .... *My proper line is in working, not in governing, still less in reigning and letting others govern.* Maxwell recognised that research work was his métier and that he was not a born ruler or governor of men.

Despite Maxwell's towering intellect and prestigious scientific achievements it was his humanity and kindness of character that made the biggest impression on his contemporaries, scientific and non-scientific alike. So often, it was these qualities that his colleagues first referred to when talking about him after his death. As William Garnett said in his obituary tribute to Maxwell:-

> *…there were other sides of his character which outshone even those scientific attainments. Such complete unselfishness and tender consideration as he exhibited for those around him, and especially for those under his control, are seldom to be met with. During the eight years that he held the Chair of Physics at Cambridge, he never spoke a hasty word, even to his attendants. His self-sacrificing devotion to those he loved was the marvel of his friends.*[xiii]

> *That marvellous interpenetration of scientific industry, philosophic insight, poetic feeling*

and imagination and overflowing humour was closely related to the profound sincerity which, after all is said, is the truest sign alike of his genius and of his inmost nature, and is most apt to make his life instructive beyond the limits of the scientific world.[xiv]

William Garnett

Being remembered for these human qualities would probably have given Maxwell the greatest pleasure. The regard and affection in which he was held by his friends was remarkable. Of his school-friends from the Edinburgh Academy, Lewis Campbell wrote his biography, Fleeming Jenkin[19] invited Maxwell to be the godfather of his son and named him after Maxwell (Bernard Maxwell Jenkin) and Tait was Maxwell's main scientific correspondent. William Garnett[20], who was Maxwell's scientific demonstrator at the Cavendish, was so impressed with Maxwell that he named his son James Clerk Maxwell Garnett.

Fleeming Jenkin

Faraday/Maxwell Theory of Electromagnetism

In electromagnetism Faraday and Maxwell recognised well before others the significance of the 'field' or 'lines of force' concept as proposed by Faraday. Faraday's analogy that, held in a state of tension, the lines of force could transmit transverse waves found resonance in Maxwell's mind. Maxwell always acknowledged that it was Faraday in 1846 who had proposed the 'electromagnetic theory of light'. Maxwell's aim was to 'mathematise' Faraday and create an acceptable theory of electricity and magnetism. Armed with vector calculus and the integral theorems of Gauss, Green, Stokes and Kelvin he was able to construct a theory which gave rise to predictions well beyond the original premises. Using results purely derived from electricity and magnetism (namely the number of electrostatic units of current which are contained in one electromagnetic unit) he showed that the velocity of propagation of the electromagnetic waves (to which his equations lead) was equal to the velocity of light derived purely from the optical experiments of Fizeau.

[19] Professor Fleeming Jenkin, MICE, LLD, FRSE, FRS (1833-1885) Professor of Engineering at Edinburgh University 1868-85. School friend of Maxwell and Tait at the Edinburgh Academy and scientific collaborator on Committee on Electrical Standards set up in 1861 by British Association for Advancement of Science. In writing to Maxwell regarding his article 'Lucretius and the Atomic Theory' which he had shown in draft to both Maxwell and Tait, Jenkin wrote "Tait has been down on me for a series of blunders and oddly enough they are none of them the same as your hits. If I had time (and spirits) I would calculate how many annotators it would take to show me that the whole is wrong from beginning to end". Jenkin must have known that Maxwell would have had a good chuckle at this irony, irony of a type of which Maxwell was himself more than capable.

[20] The former President of IMA, Professor Julian Hunt, FRS, now Lord Hunt of Chesterton, is a direct descendent of William Garnett.

In October 1861 he wrote to Faraday :-

> *……I have determined the velocity of transverse vibrations. The result is 193,088 miles per second (deduced from electrical & magnetic experiments). Fizeau has determined the velocity of light as 193,118 miles per second by direct experiment. The co-incidence is not merely numerical. I worked out the formulae in the country* (author's note:- presumably at Glenlair, Maxwell's home in Scotland) ………*and I think we have strong reason to believe………that the luminiferous and the electromagnetic medium are one.*

At the same time Maxwell wrote to his Trinity friend C. J. Monro[21]:-

> *…..which is an argument* (author's note:- by this Maxwell is referring to the equality of the velocity of transverse vibrations of the electromagnetic medium and the observed velocity of light) *for light being transverse undulations of the electromagnetic medium.*(author's note:- in his reply Monro called this *a brilliant result)*

In 1861, his paper 'On Physical Lines of Force' Maxwell invents a mechanical model (using fixed rotating cylinders with ball bearings between the cylinders, the latter being also free to rotate and move laterally acting as idle wheels) to show how a varying magnetic field (the speeding up or slowing down of the rotation of the cylinders – i.e. their angular acceleration) can produce an electric field (lateral motion of the ball bearings in addition to their rotation) and how, vice versa, a varying electric field (lateral movement and rotation of the ball bearings) can produce a magnetic field (speeding up or slowing of the cylinders). By the two effects operating simultaneously waves can be produced. In the paper he says:-

> *I have deduced …..and have shewn that the elasticity of the magnetic medium in air is the same as that of the luminiferous medium, if these two …media are not rather one medium*
>
> *The velocity of transverse undulations in our hypothetical medium, calculated from the electromagnetic experiments of Kolrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of Fizeau, that we can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena..*

It is clear that by late 1861 both Maxwell and Faraday knew 'in their bones' that light was an electromagnetic phenomenon but it took another 27 years for the first experimental demonstration of electromagnetic waves in the laboratory.

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[21] C. J. Munro, 38^{th} Wrangler and 8th Classic 1855 and Fellow of Trinity in 1856.

Maxwell derived the actual wave equations for the electromagnetic field, in his paper, published in 1865, *'A Dynamical Theory of the Electromagnetic Field'*. In modern notation Maxwell's equations are as follows:-

E is the electric field, ***D*** is the electric field allowing for dielectric material, ρ is charge volume density (all in e.s.u. units) and ***H*** is the magnetic field and ***B*** is the magnetic field allowing for the magnetic material, j is the current density (all measured in e.m.u. units) and C represents the ratio of electromagnetic to electrostatic units of current (a number that Maxwell had shown to have the dimensions of a velocity - a seminal paper on the dimensions of electrical quantities having been written by Maxwell and Jenkin[xv]).

$$\nabla \wedge \boldsymbol{H} = 4\pi j + \frac{1}{\mathrm{C}}\frac{\partial \boldsymbol{D}}{\partial t}$$ Oersted/Ampère plus Maxwell

$$\nabla \wedge \boldsymbol{E} = -\frac{1}{\mathrm{C}}\frac{\partial \boldsymbol{B}}{\partial t}$$ Faraday's Law of induction.

$$\nabla . \boldsymbol{D} = 4\pi\rho$$ Poisson/ Coulomb's inverse square law

$$\nabla . \boldsymbol{B} = 0$$ No magnetic monopoles exist

In a vacuum these equations reduce to:-

$$\nabla . \boldsymbol{E} = 0 \quad \nabla . \boldsymbol{H} = 0 \quad \nabla \wedge \boldsymbol{H} = \frac{1}{\mathrm{C}}\frac{\partial \boldsymbol{E}}{\partial t} \quad \nabla \wedge \boldsymbol{E} = -\frac{1}{\mathrm{C}}\frac{\partial \boldsymbol{H}}{\partial t}$$

Using the identity $\nabla \wedge (\nabla \wedge \boldsymbol{V}) = \nabla(\nabla . \boldsymbol{V}) - \nabla^2 \boldsymbol{V}$ (or, in words, curl curl equals grad div minus del squared – the word 'curl' having been suggested by Maxwell[xvi]) and taking ***E***=(E,0,0) and ***H***= (0,H,0), we have the transverse wave equations $\frac{1}{C^2}\frac{\partial^2 E}{\partial t^2} = \frac{\partial^2 E}{\partial z^2}$ and $\frac{1}{C^2}\frac{\partial^2 H}{\partial t^2} = \frac{\partial^2 H}{\partial z^2}$.

From the extraordinary co-incidence that the velocity of these transverse electromagnetic waves (C, a ratio derived purely from electromagnetic experiments) was, within experimental error, equal to the observed velocity of light, c, he concluded that:-

> *This velocity is so nearly that of light, that it seems we have strong 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.

This conclusion of 1865 (i.e. that C=c and light is an electromagnetic wave) was the most stunning triumph of theoretical physics in the 19^{th} century.

The truth of the Faraday/Maxwell theory of electromagnetic phenomena, namely that these can be described by electric and magnetic fields propagated in space at finite velocity and governed by certain mathematical equations, changed our perception of the world. The theory is now universally accepted and it is forgotten that there were powerful advocates at the time of several alternative theories, which might be called the 'German Theories', of Weber, the Neumanns, Riemann and Lorenz. These theories were founded on ‘action at a distance', a physical hypothesis which was entirely alien to the Faraday/Maxwell theory. Gauss abandoned his efforts to develop a theory of electro-magnetism since he could not derive a satisfactory theory of the propagation of 'electric action in time' which he felt would ultimately be found to be the keystone of electrodynamics. Gauss was right and the way in which Faraday/Maxwell theory did this provided the keystone.

It is understandable that the competing German Theories caused Maxwell a certain amount of frustration and in a paper *On a method of making a direct comparison of Electrostatic with Electromagnetic force; with a Note on the Electromagnetic Theory of Light* of 1868 he set out the four premises on which his electromagnetic theory depended. One may have little doubt that he did this in order to simplify the theory as much as possible and in order that this lucid exposition of the theory would carry conviction among his peers. The four basic premises on which the Electromagnetic Theory depended were set out by Maxwell as follows:-

(i) *If a closed curve is drawn embracing an electric current, then the integral of the magnetic intensity taken round the closed curve is equal to the current multiplied by 4π (Oersted/Ampère).*

(ii) *If a conducting circuit embraces a number of lines of magnetic force and if, from any cause whatever, the number of these lines is diminished, an electromotive force will act round the circuit, the total amount of which will be equal to the decrement of the number of lines of magnetic force in unit of time (Faraday).*

(iii) *When a dielectric is acted on by an electromotive force it experiences what we call electric polarisation. Within the dielectric there is a displacement of electricity - the displacement being proportional to the electromotive force at each point (Faraday).*

(iv) *When the electric displacement increases or diminishes the effect is equivalent to that of an electric current (Maxwell).*

Maxwell explains premise (iv) in greater detail:-

> *According to this view, the current produced in discharging a condenser is a complete circuit and might be traced within the dielectric itself by a galvanometer properly constructed. I am not aware that this has been done so that this part of the theory, though apparently a natural consequence of the former, has not been verified by direct experiment. The experiment would undoubtedly be a very delicate and difficult one.*

Based on these four premises Maxwell then proceeded to derive the wave equations for the electromagnetic field showing that, on the basis of known fundamental electric and magnetic constants, the velocity of these electromagnetic waves in the hypothetical aethereal medium was equal to that of the known velocity of light.

In his 1870 address as President of the Mathematics and Physics Section of the British Association for the Advancement of Science, Maxwell described the position as follows:-

> *According to a theory of electricity which is making great progress in Germany, two electrical particles act on one another directly at a distance, but with a force which, hinted at by Gauss* (see reference above to Gauss ultimately abandoning his efforts) *and developed by Riemann, Lorenz and Neumann, acts not instantaneously but after a time, depending on the distance. The power with which this theory, in the hands of these eminent men, explains every kind of electrical phenomena must be studied in order to be appreciated.* (a touch of pawky Maxwellian humour here!)
>
> *Another theory of electricity which I prefer, denies action at a distance and attributes electric action to tensions and pressures in an all pervading medium, these stresses being the same in kind with those familiar to engineers, and the medium being identical with that in which light is supposed to be propagated.*
>
> *Both these theories are found to explain not only the phenomena by the aid of which they were originally constructed but other phenomena, which were not thought of or perhaps were not known at the time; and both have independently arrived at the same numerical result, which gives the absolute velocity of light in terms of electrical quantities.*

Professor Dyson in his essay 'Why is Maxwell's Theory so hard to understand?'[xvii] refers to Maxwell being "infuriatingly modest" in merely calling his theory "*Another theory of electricity which I prefer".*

In the early 1870s it was clear that Maxwell was again somewhat frustrated by the scientific community not giving sufficient attention to comparing the German Theories with the Faraday/

Maxwell theory and it may be this that was the motivating force for Maxwell to produce his famous textbook, 'A Theory on Electricity and Magnetism' in 1873. In the introduction to his book Maxwell wrote as follows:-

Maxwell in later life

Great progress has been made in electrical science, chiefly in Germany, by cultivators of the theory of action at a distance .... the electromagnetic speculation carried out by Weber, Riemann, F. and C. Neumann, Lorenz etc is founded on the theory of action at a distance ..... These physical hypotheses however, are entirely alien to the way of looking at things which I adopt..... It is exceedingly important that the two methods should be compared.......I have therefore taken the part of an advocate rather than a judge.

Given that Maxwell was writing his famous book as an advocate of a new theory it is remarkable that his book should stand today almost as a textbook – albeit somewhat old fashioned – treatment of the subject. Surely only with Newton's Principia can another example be found of a new subject being treated by the originator with an assuredness that has so remarkably stood the passage of time.

A degree of luck

Maxwell recognised that it was not always given, even to the ablest of men, to find the truth. In his inaugural address as the new Cavendish Professor he said when speaking about the history of science:-

> *But the history of science is not restricted to the enumeration of successful investigations. It has to tell of unsuccessful enquiries, and to explain why some of the ablest men have failed to find the key of knowledge…*

It is clear that Maxwell had luck on his side.

Following the final construction of the Cavendish Laboratory in 1874, it might have been expected that in the five years left to him Maxwell would have used the galaxy of talent which he had as research students[22] to discover if there other radiations apart from light and radiant heat. It is open to question whether, if Maxwell had lived until 1888 he would have beaten Hertz to their discovery. It is interesting that, in 1879 or 1880, David Hughes, the inventor of the microphone, had both produced and detected radio waves but Sir George Stokes[23] had failed to identify them as such thinking that

[22] Research students who became FRSs included Sir Richard Glazebrook, Sir Ambrose Fleming, Sir Arthur Schuster, Sir William Shaw, William Hicks, John Poynting and Charles Heycock

[23] Sir George Stokes, FRS , Senior Wrangler 1841, Lucasian Professor Mathematics at Cambridge, President of Royal Society.

what he was observing was ordinary induction. It seems unlikely that Maxwell would have also failed to detect the significance of Hughes experiments but by this time Maxwell was either seriously ill (and it seems unlikely that Hughes' result was communicated to him) or had already succumbed to his fatal cancer.

In 1888, Hertz was able to show electromagnetic waves, of a frequency we would now call radio waves of 6 cm. wavelength, being transmitted across the laboratory (the wavelength of visible light is between 0.44 and 0.77 times 10^{-6} cms. i.e. very much shorter than that for wireless communication).

This was the most stunning triumph of experimental physics in the 19^{th} century.

One can be sure that, had he lived, Maxwell would have been delighted by the achievement of Hertz, even if he had not made the experiments himself. Indeed, had he lived a normal life span (according to the article on *Annuities* by T.B. Sprague[24] in the 9^{th} Edition of the Enclopaedia Britannica, whose scientific editors were Maxwell and Huxley, a person aged 48, as Maxwell was at the time of his death, could expect to live another 20 years on average) Maxwell would have witnessed the gradual unveiling of the whole glory of the electromagnetic spectrum from radio waves to ultra-violet rays, to X-Rays, etc. One can only imagine what Maxwell would have felt about these events and what contribution he might have made to their further advance. In an article for the 1878 (9^{th}) Edition of the Encylopaedia Britannica entitled *Ether* and in a letter of 1879 to D. P. Todd, Director, Nautical Almanac Office, Washington, USA Maxwell proposed a method of measuring the passage of the Earth through the *Ether* and himself had tried an alternative method using a spectroscope. Morley, in 1881, in carrying out an experiment of the alternative type tried by Maxwell, derived a negative result and in 1889, Fitzgerald, and in 1892, Lorentz, in order to explain this negative result, made the extraordinary suggestion that moving rods contract in the direction of motion by an amount which depended on the ratio of the square of the velocity of the rod to the square of the velocity of light. The explanation that Maxwell might have tumbled to, if he had been alive to hear of these results, does not bear thinking about!

Acknowledgements

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[24] T. B. Sprague MA, LLB, FIA, FFA, FRSE (1830-1920) Senior Wrangler and First Smith's Prizeman, 1853 (the year between Maxwell and Tait). Actuary to Equity and Law (succeeding the famous mathematician J J Sylvester) then General Manager of Scottish Equitable. President of the Institute of Actuaries and later President of the Faculty of Actuaries. The greatest actuary of his day.

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[v] *Obituary* (see above).

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