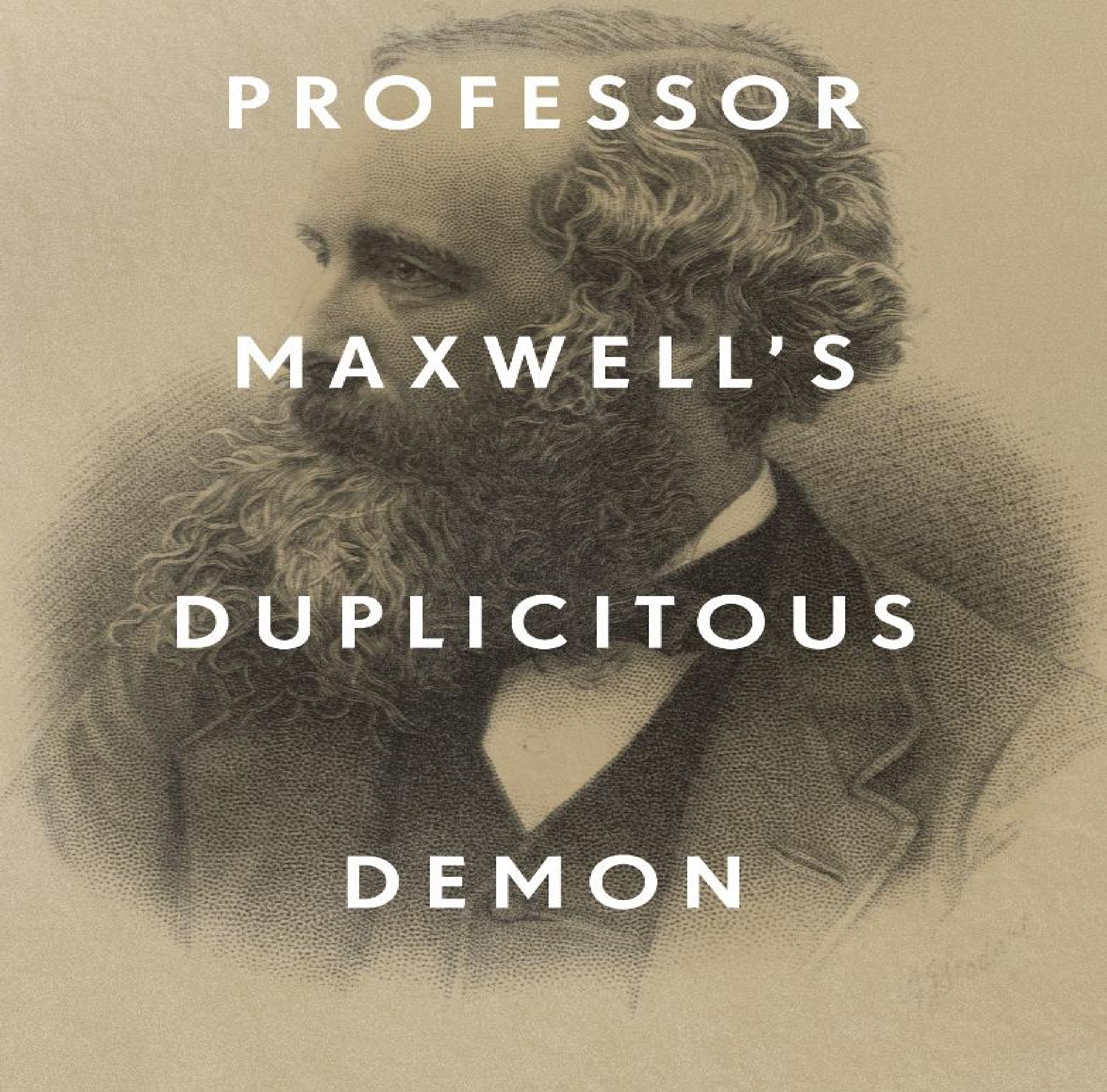
THE LIFE AND SCIENCE OF
JAMES CLERK MAXWELL



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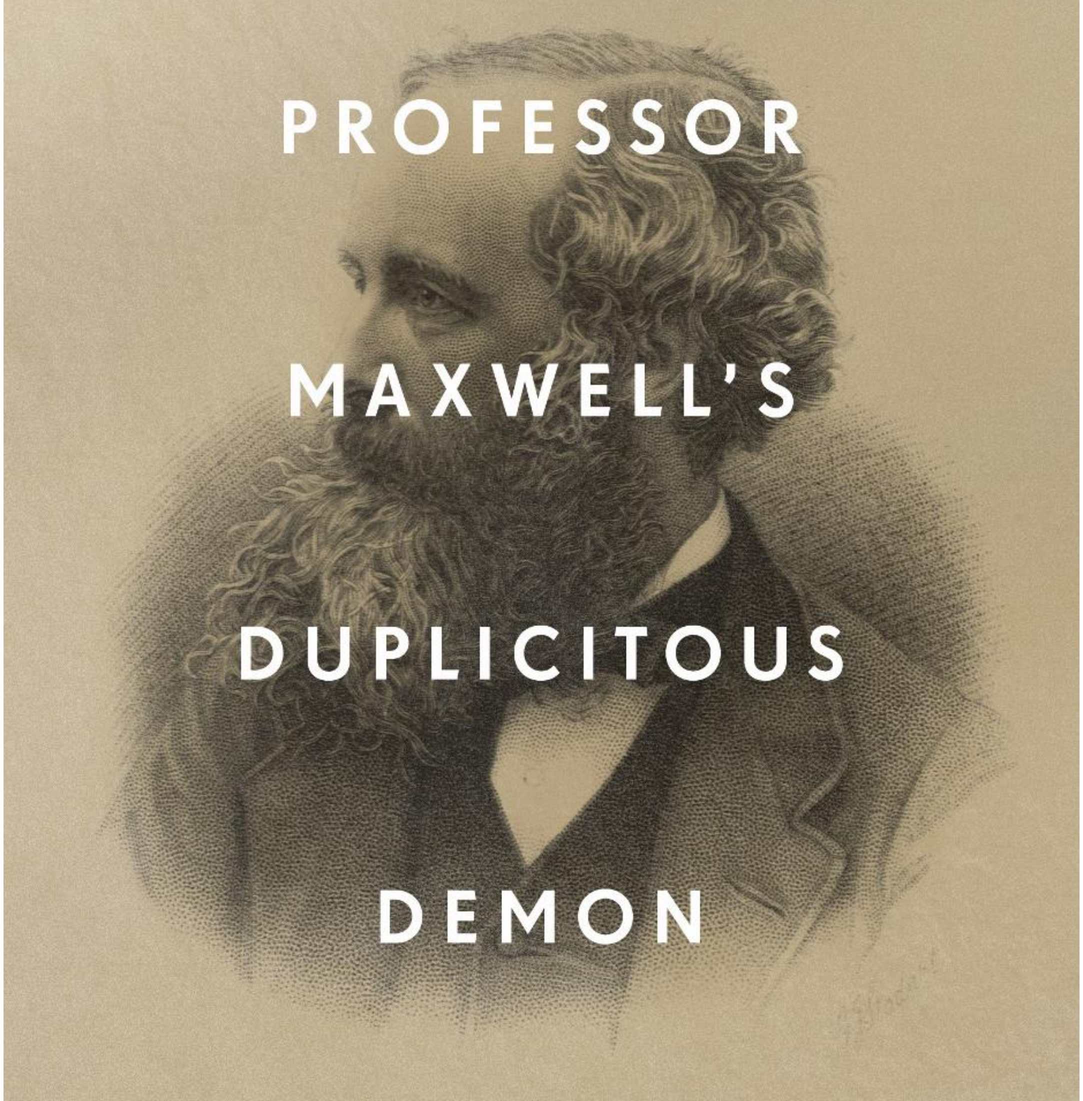

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ICON

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For Gillian, Rebecca and Chelsea

Acknowledgements

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Thanks also to the various experts who have written on James Clerk Maxwell, and to the help from David Forfar and John Arthur of the James Clerk Maxwell Society.

Demonic Interlude I

In which the demon is summoned

I appreciate that demons rarely feature in popular science titles. Not even in books on the god particle,[*] which is somewhat remiss. Yet a demon I am. I was originally summoned into being by the eminently respectable, God-fearing Scottish professor James Clerk Maxwell, and proclaimed to be a demon by his fellow Scot and physicist William Thomson. I was born – as are so many things in your universe – out of the second law of thermodynamics.

This 'law of thermodynamics' business may sound boringly mired in the steam age, and that's certainly how it originated. But the second law determines how the universe works. Strictly speaking, incidentally, the second law is the third law, as an extra one was added in at the top of the list after the first two were proclaimed, but to avoid – or possibly cause – confusion, the late-comer was named the zeroth law. The second law can be phrased in two ways, either of which sounds perfectly innocuous. Yet in those simple statements lie the foundations of reality and the doom of everything.

It's the second law that decides that effect follows inevitably from cause. It's the second law that ensures that books on perpetual motion machines remain on the fiction shelves in the library. Indeed, it's the second law that determines the flow of time in your world (it's far more flexible in mine). If you could prove that the second law could be broken, you would set chaos loose to reign in the world. As a demon, this sounds an attractive proposition – and it's appropriate, as breaking that law is exactly what I was created to do.

How does my charge sheet read? You can either say that the law states that heat passes from a hotter to a colder body, or that entropy – the measure of the disorder in a system – always stays the same or increases. But I was brought into being to challenge this law. Do you think it doesn't matter if some piddling law of physics is broken? This is the law that explains why a dropped glass breaks and never unbreaks. It makes it possible for life to exist on Earth and it predicts the end of the universe. And without it, the many engines that your lives depend on, from cars to computers, would fail. So, don't disrespect the second law.

The early twentieth-century English physicist and science writer Arthur Eddington[†] said: 'If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations [James Clerk M's masterpiece that describe how electromagnetism works] – then so much the worse for Maxwell's equations. If it is found to be contradicted by observation – well these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in the deepest humiliation.'

Which raises the curtain for me. My sole purpose in life is to show that the second law of thermodynamics can indeed be broken. I enable heat to travel from a colder to a hotter place. Uncomfortably for a demon, I am able to *reduce* the level of disorder in the world. And if I can truly achieve this, it's not me, but every physicist since Victorian times who must collapse in the deepest humiliation.

I am, as Churchill might have put it, a riddle, wrapped in a mystery, inside an enigma. Whether anyone has been able to find the key to defeat me remains to be seen in the pages to come. But first, we need to discover the young James Clerk Maxwell.

At the risk of sounding like Frankenstein's monster, prepare to meet my creator.

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[*] For those not familiar with this term, it is a nickname for the Higgs boson, which came to public attention when it was discovered using the Large Hadron Collider at CERN in 2012. Amusingly for those of us with demonic tendencies, physicist Leon Lederman wanted to call his book on the search for the particle *The Goddamn Particle,* because the Higgs was such a pain to pin down. The publishers objected that this might be considered too irreverent by the public and resorted to the misleading alternative of *The God Particle,* which really winds up most physicists.

[†] A man totally lacking in the wondrous beard sported by each of his Scottish counterparts.

Chapter 1

Not a little uncouth in his manners

There was nothing to suggest the coming of a demon in James Clerk Maxwell's early life. We ought to get that convoluted name untangled first of all. Over the years, those writing about him have never been sure what to call him. Some have resorted to Clerk Maxwell or even an approach he would never have countenanced, the hyphenated Clerk-Maxwell, but his name was not really double-barrelled and 'Maxwell' does the job far better.

Maxwell's father was originally called John Clerk (pronounced to rhyme with 'park'). This family, existing on the boundary between the upper middle class and the aristocracy, had a complex history. One of Maxwell's distant ancestors, another John Clerk, had bought the vast lowland Scottish estate of Penicuik, and with it a baronetcy[*] back in 1646. His second grandson married an Agnes Maxwell, who brought with her the equally impressive estate of Middlebie. Over the years (and quite a lot of intermarrying of cousins) the name 'Clerk' was always associated with Penicuik and Maxwell with Middlebie – and when appropriately named cousins came together, they sometimes took the name Clerk Maxwell.

By Maxwell's father's time, Middlebie was only a shadow of its former self, a 'small' 1,500-acre (600-hectare) holding, which is why their estate house ended up a good 30 miles from the town of Middlebie itself. The rest of the estate was sold off to cover some risky speculation in mining and manufacturing by Maxwell's great-grandfather. John Clerk's older brother George was the principal heir, but part of John's inheritance was what was left of the Middlebie estate. This was not an act of generosity on George Clerk's part. The estate was entailed such that Middlebie and Penicuik could not be held together – otherwise, he would likely have held on to the whole thing. Splitting estates was considered bad form. When John Clerk received this new position, he took the traditional laird's name, tacking 'Maxwell' on after Clerk.

Edinburgh and Glenlair

James Clerk Maxwell was born on 13 June 1831, at his parents' home, 14 India Street, Edinburgh – now, appropriately enough, the home of the James Clerk Maxwell Foundation. This was a three-storey townhouse on a cobbled street set back from Queen Street, one of the three parallel roads that form the heart of the city. Maxwell was a late and, in all probability, a spoiled child. His mother, Frances Cay before marriage, had lost her first child Elizabeth as a baby. Frances was almost forty when Maxwell turned up.

Maxwell's father, John, had been a successful advocate (the Scottish equivalent of a barrister), but by the time Maxwell was two, John Clerk Maxwell had settled into his new role of country landowner. The family left the Edinburgh house behind, still owning it but renting it out throughout Maxwell's life. Middlebie had no grand manor, unlike brother George's imposing Palladian-style Penicuik House,[†] but John and Frances arranged for a relatively humble home, Glenlair, to be built for them on the farmland known as Nether Corsock.

The social distance between the lively city of Edinburgh and the rural isolation of Middlebie was far more than the 80 or so miles between them suggests. Edinburgh was a modern Victorian city, encouraging scientific and literary thought. Middlebie might as well have remained stuck two centuries in the past. And that 80 miles was made to seem greater still by the difficulties of travelling in rural parts of Scotland. The route, via Beattock, took two complete days, needing a stop along the way. The vehicles available were hardly state-of-the-art. In the biography of Maxwell written just three years after his death by Lewis Campbell, a lifelong friend since school who became a professor of classics, and William Garnett, another friend who was an English electrical engineer, it is noted that:

> Carriages in the modern sense were hardly known to the Vale of Urr. A sort of double-gig with a hood was the best apology for a travelling coach, and the most active mode of locomotion was in a kind of rough dog-cart, known in the family speech as a 'hurly'.

It's indicative of John's nature – which seems to have been inherited by his son – that when outbuildings were added to the house in 1841, not only did John plan what was required, he drew up the working plans for the builders to use. Although he was a lawyer, according to Maxwell's early biographers, when not on a case, John 'dabbled between-whiles in scientific experiment'. He even published a paper in *The Edinburgh New Philosophical Journal* on an automated printing device entitled 'Outline of a plan for combining machinery with the mechanical printing-press'. John Clerk Maxwell was exactly the right kind of father to encourage his son to take an interest in the natural world.

Maxwell's first eight years must have seemed idyllic for a well-off child of the period. His parents allowed him remarkable freedom, neither preventing him from mixing with the local farm children, nor beating out of him the thick Galloway accent he picked up from his friends, which surely must have put a strain on their class-driven sensibilities. In fact, they seem to have been unusually unstuffy for a Victorian family.[‡] Theirs was a home where there was little room for formality, but plenty of humour, an approach to life that would later stand Maxwell in good stead.

The estate combined the contrasting terrains of moorland and farmland and ran alongside the curving banks of the River Urr. A small burn feeding the Urr ran at the edge of the meadow beyond the house. By digging out a hollow in the bed of the burn, the Maxwells provided themselves with a swimming pool. Though it would have been freezing cold even at the height of summer, it was no doubt a great attraction for the young Maxwell.

Given their relative wealth, the Maxwells could have readily afforded a tutor for their son. It's telling that when Mary Godwin (later Mary Shelley), the author of *Frankenstein,* was young, her family was described as being of a 'very restricted income', yet her brothers were sent to boarding school and she had 'tutors in music and drawing as well as a governess'. The Maxwell family was far better off than the Godwins, but displaying an unusual interest in her child for a wealthy parent of the day, Frances looked after Maxwell's schooling herself. Things would soon change, though. The death of Frances from abdominal cancer in 1839, aged just 47, must have caused the bottom to drop out of the eight-year-old James's world.

While his father, John, had certainly gone along with Frances' wish to devote her time to raising the boy, he either wasn't able or didn't wish to do the same himself. It was one thing to let the young Maxwell play with his local contemporaries, but the nearby schools were very limited in their educational standards and John could not see his son attending one. For a while, he tried out a young man as a tutor, just sixteen when he took on the job. The teenager had neither the talent nor the experience to keep the bright and curious young Maxwell interested and his efforts failed miserably. Maxwell became difficult and would not accept his lead.

The tutor (whom Maxwell later felt it inappropriate to name) was also rough, even by the standards of the period. Maxwell's experience apparently included being 'smitten on the head with a ruler and [having] one's ears pulled 'til they bled'. As his contemporary biographers who knew him well put it, the effects of this harsh treatment remained 'in a certain hesitation of manner and obliquity of reply which Maxwell was long in getting over, if, indeed, he ever quite got over them'.

In this difficult time, Maxwell's release was the chance to roam free on the estate, observing the natural world close-up. This is something that his father had always encouraged, and Maxwell took a particular interest in the variations in colour he saw in nature. He was especially interested in crystals, which fascinated him in the way that their colours changed as they were put under pressure. His father's friend, Hugh Blackburn, a professor from Glasgow University, added a novel delight, allowing Maxwell to help him launch a series of hot air balloons from the Glenlair estate.

Maxwell had the usual youngster's excitement and interest in everything around him. According to the early biography, among his favourite phrases were 'Show me how it doos', and 'What's the go o' that[§]?' This enthusiastic curiosity about the world around us seems natural in youth – speak to children at primary school and you can't miss the way that they are enthused by science – but many lose that sense of wonder during their secondary school years. Maxwell held on to a childlike fascination for the rest of his life.

The Academy

It was clear, though, that the attempt to use the failing tutor to deal with Maxwell's education was a disaster that could not be sustained; Frances' sister, Jane Cay, who lived in Edinburgh, came to the rescue. She suggested to John that Maxwell could come to live in the city with John's unmarried sister Isabella. Isabella's house was ideally placed to walk to the prestigious Edinburgh Academy – Maxwell could get a decent education and live under the supervision of his aunts during term time, then return to roam free on the Glenlair estate in the holidays. This wasn't, however, a matter of his father dismissing Maxwell solely to his aunts' care – in the winter particularly, John Clerk Maxwell spent regular evenings in Edinburgh with his son.

Glenlair wasn't a grand aristocratic country house – it was effectively a large farmhouse,[¶] though Maxwell would extend it considerably in the 1860s. It was big enough to entertain and to have space for Maxwell's scientific ventures when he was older, but on a scale where it still felt homely. Glenlair would remain an important focal point for Maxwell throughout his life.[‖]

Despite the suggestion that he was rendered hesitant by the bad treatment of his tutor, Maxwell seems not to have been a sensitive child. And it's just as well, given his reception when he was sent to the Edinburgh Academy for the first time at the age of ten. Schoolchildren have never been slow to pick on those who are different, and Maxwell offered them rich opportunities for mockery, especially as the first-year class was full and so he was plunged straight in with older, better-established boys.

It wasn't just his accent, marking him out as provincial, that made the young Maxwell a target for mockery. He arrived at the school dressed in a combination of tweed jacket, frilly-collared shirt and brass-buckled shoes that were guaranteed to make him look like a mongrel throwback from fashion history. Maxwell reported that he returned home on the first day with his tunic reduced to rags, though he appeared to find this more amusing than frightening.

The Academy was a relatively new school, which had been open for just eighteen years when Maxwell first attended. It was set up to compete with the classical education provided by English public schools. As such, it had a focus on giving its pupils independence and hard discipline alongside a rigid curriculum that focused intensely on the classics with perhaps a spot of maths; there was very little science. As the father of the founder of the Scouting movement Robert Baden-Powell commented in 1832: ‘Scientific knowledge is rapidly spreading among all classes except the higher, and the consequence must be, that that class will not long remain the higher.’

Having such a limited curriculum seemed to be a mark of pride in the public schools. John Sleath, High Master of the prestigious St Paul’s School in London during the early part of the nineteenth century, wrote to his parents: ‘At St Paul’s School we teach nothing but the classics, nothing but Latin and Greek. If you want your boy to learn anything else you must have him taught at home, and for that purpose we give him three half-holidays a week.’

This was a period when public schools were hardly centres of excellence. For example, the pupils of Rugby School took their masters prisoner at sword-point and were overcome after the reading of the Riot Act resulted in an armed rescue. With very little parental supervision, many schools, even the big names, provided a shoddy education in return for their fees. At Eton, to keep the costs of teaching staff down, boys could be taught in groups that were nearly 200 strong. While conditions were not so extreme at Edinburgh, in Maxwell’s early years, classes could have 60 or more pupils.

However, reforms were underway in the school system, with more opportunity to have a ‘modern’ side as an alternative to the classics, and Edinburgh Academy was arguably more up-to-date in its approach than many of its older English equivalents. Even so, not used to the pressures of school life, having always had the time to think at his own pace, Maxwell came across as slow to learn. A combination of this and his rural accent earned him the nickname Dafty, which stuck even when it became clear that he was extremely academically gifted. Inevitably, though, so far away from his familiar home and the estate, it took Maxwell a while to bed in. A classmate called him ‘A locomotive under full steam, but with the wheels not gripping the track’.[**]

Maxwell was not exactly a loner at school, but simply seemed to carry on as he had before, doing his own thing – if others wanted to join him, that was fine, but he seemed in no hurry to conform. Thankfully, his aunts quickly provided him with more conventional clothing when it was realised that his dress appeared more than a little eccentric. Maxwell certainly seemed comfortable when at home at Isabella’s house, 31 Heriot Row, a handsome four-storey grey stone townhouse with a small park out the front. He had a chance to explore both the house’s excellent library and what the natural world of Edinburgh had on offer for him to observe. Though the school took boarders, it always had day boys as well, including Maxwell.

With time, Maxwell’s limited social contact at school grew. A like-minded student who did not consider it embarrassing to be academic, Lewis Campbell moved to live near Heriot Row, and soon the two boys spent their journeys to and from school together, developing a strong bond that would last a lifetime. They had now reached an age when the school added mathematics to its limited classical curriculum – something omitted in the first two years – and Maxwell not only found that he excelled at the subject, but that he and Campbell shared a love of maths (and a certain amount of rivalry in their ability to solve mathematical problems).

Once this barrier was broken through, it seemed easier to gain friends who had an interest in science and nature, notably Peter Tait. Another lifelong friend, Tait would himself go on to become one of Scotland’s leading physics professors, in his early career even managing to beat Maxwell to take an academic post. At school, Maxwell came second to Tait in mathematics in 1846 (at the time his best subjects were scripture, biography and English verses) but pulled ahead in 1847. When secure in his little group with Tait and Campbell, Maxwell loved the opportunity to puzzle through mathematical and physical challenges, something that inspired him at the age of fourteen to come up with his first academic paper – though strangely his investigations owed as much to the arts as the sciences.

The young mathematician

Maxwell’s father regularly took him to meetings of both the Royal Society of Edinburgh and the Royal Scottish Society of Arts (RSSA). It was here that Maxwell became familiar with the work of the local artist David Ramsay Hay. In Hay’s philosophy, Maxwell found a point of view that was similar to his own – Hay both delighted in the beauty of nature and wanted to apply scientific measurements to it. Maxwell would later spend much effort on the nature of colour and colour vision – Hay was interested in a mathematical representation of the beauty of colour. But, equally, Hay was fascinated by the mathematics of shape and it was here that Maxwell's paper seems to have drawn its inspiration. Hay would later give a paper at the RSSA on 'Description of a machine for drawing a perfect egg-oval'. Maxwell's youthful paper was on the subject of curves such as ovals that can be drawn using a pencil, a piece of string and pins.

Maxwell's experimental apparatus resembled a primitive version of the popular 1960s toy Spirograph. By placing pins through a sheet of paper into a piece of card and looping a length of string around the pins, it's possible with some care to draw simple geometric shapes. With a single pin, you get a circle. Two pins produce the dual foci of an egg-like ellipse. This much was standard school fare, but Maxwell took the investigation significantly further. He looked at what would happen with the string tied to one or more pins and the pencil, allowing for different numbers of loops around each of the two pins, and worked out an equation that linked the number of loops, the distance between the pins and the length of the string.

Maxwell shared his work with his father, who showed it to his friend James Forbes, Professor of Natural Philosophy[††] at Edinburgh University. Fascinated by this precocious piece of work, Forbes brought in a mathematician from the university, Philip Kelland, who checked through the literature for precedents.[‡‡] Although some similar work had been done by the French scientist and philosopher René Descartes, Kelland discovered that not only was Maxwell's approach simpler and easier to understand than Descartes', it was more general than the results that Descartes had published.

Given the originality of young Maxwell's work, Forbes was not going to let the effort go by rewarded with nothing more than a pat on the head. He managed to present Maxwell's paper, now grandly titled 'Observations on Circumscribed Figures Having a Plurality of Foci, and Radii of Various Proportions', at the Royal Society of Edinburgh in April 1846. The fourteen-year-old Maxwell could not present the paper himself as he was both too young to do so and not a member, but he had regularly attended Royal Society meetings with his father and was present to hear his work read. The paper was well received and cemented Maxwell's growing feeling that his future lay in science and mathematics. It is too long (and, frankly, too boring) to reproduce here, but here is the opening sentence to get a feel for the young Maxwell's precocious (and somewhat long-winded) output:

> Some time ago while considering the analogy of the Circle and the Ellipsis – and the common method of drawing the latter figure by means of a cord of any given length – fixed by the ends of the foci – which rests on the principle, that the sum of the two lines drawn from the foci to any point in the circumference is a constant quantity, it occurred to me that the *Sum* of the Radii being constant was the essential condition in all circumscribed figures, and that the foci may be of any number and the radii of various proportions.

Maxwell must have been delighted to see as august a body as the Royal Society of Edinburgh begin the description of his work with: 'Mr Clerk Maxwell ingeniously suggests the extension of the common theory of the foci of the conic sections to curves of a higher degree of complication in the following manner:—.' Although Maxwell continued with his general education, he began to read voraciously from the books and papers of the scientific greats, developing a particular affection for the down-to-earth approach of the self-taught English scientist Michael Faraday, who had become a leading light of the Royal Institution in London by the time Maxwell was at school.

Churchman and country squire

We tend these days to make a clear distinction between scientific study and religious beliefs, but Maxwell came from the last generation in the British tradition where there was no feeling of conflict between the two. Like many of the scientific greats before him (including Faraday and, in his own strange way, Newton), Maxwell had a deeply held religious faith. On his breaks from Edinburgh, back home in Glenlair, the family and their servants would join together each day in prayer, and the entire household made the five-mile trek each Sunday to attend the Presbyterian Church of Scotland's Parton Kirk – where his mother was buried, in a grave inside the ruins of the Old Kirk that would eventually also hold his father, Maxwell himself and Maxwell's widow. While he was in Edinburgh, his Aunt Jane made sure this observance was kept up, taking him to attend both Episcopal and Presbyterian churches, cementing a religious faith that remained strong throughout Maxwell's life.

Regular breaks at Glenlair would remain an essential for Maxwell, whether he was a student or professor. It was a total break from the bustle of the city or the rigours of an academic institution. In his obituary for Maxwell, his friend Peter Tait would comment of his schooldays:

> [H]e spent his occasional holidays in reading old ballads, drawing curious diagrams, and making rude[§§] mechanical models. His absorption in such pursuits, totally unintelligible to his schoolfellows (who were then quite innocent of mathematics), of course procured him a not very complimentary nickname …

Wherever he worked as an adult – he would later be based in Aberdeen, London and Cambridge – Maxwell's summers would be spent on the Glenlair estate. When at home, in almost all respects, Maxwell would be a typical country gentleman of the period – except for his unusual enthusiasm for and delight in nature. Where most of his contemporaries enjoyed nothing better than a mass slaughter in the shooting season, Maxwell never took part in hunting and shooting.

Even though he continued to live at 31 Heriot Row with Aunt Isabella, the influence of Maxwell's family was about to wane, as he transferred from the Academy to Edinburgh University at the age of sixteen. It might seem after his clear demonstration of mathematical originality that he would have already set his sights on a mathematical or scientific career, but this was a period when professional scientists like Michael Faraday and Faraday's former boss Sir Humphry Davy were in the minority. The word 'scientist' was only coined in 1834 when Maxwell was three, and took a while to settle in. Some alternatives of the period were 'scientician' and 'scientman'. Maxwell is often considered one of the first truly modern scientists.

It was not that landed gentry did not partake in science. It was just that someone of Maxwell's status was far more likely to perform their scientific work as an amusement, a hobby to pass the time – so Maxwell's original intention had been to follow his father in entering the law. However, Edinburgh University was still using the traditional broad approach of the ancient university curricula, so had both mathematical and natural philosophy (science) content in its degree course. It's notable from a letter that Maxwell wrote to Lewis Campbell in November 1847 that the maths and science were the parts that dominated his interest:

> As you say, sir, I have no idle time. I look over notes and such like until 9.35, then I go to Coll., and I always go one way and cross streets at the same places; then at 10 comes

> Kelland [mathematics lecturer, Philip Kelland]. He is telling us about arithmetic, and how the common rules are the best. At 11 there is Forbes [Maxwell's father's friend, the physics professor], who has now finished introduction and properties of bodies, and is beginning Mechanics in earnest. Then at 12, if it is fine, I perambulate the Meadows; if not, I go to the Library and do references. At 1 I go to Logic [with Sir William Hamilton].

The only passing mention of the classics in his letter is to say, 'I intend to read a few Greek and Latin [textbooks] beside'. Classics was a compulsory part of the majority of university courses. There is no mention at all of the law – this would be picked up after his university degree.

Perhaps most importantly, Maxwell had access to the university's limited laboratory equipment (likely to be in an outhouse, as there was no purpose-built lab at Edinburgh in 1847) when he had the time, encouraged by family friend Professor James Forbes. It was here, and in a workroom at Glenlair during the long summer vacation, as much as in the formal training he received at the university in logic and natural philosophy, that Maxwell's unstructured, youthful scientific curiosity was forged into a first-class scientific mind.

The university life

At the time, some of the personal oddities that had got Maxwell mocked at school still remained part of his nature. His early biographers note: 'When he entered the University of Edinburgh, James Clerk Maxwell still occasioned some concern to the more conventional among his friends by the originality and simplicity of his ways. His replies in ordinary conversation were indirect and enigmatical, often uttered with hesitation and in a monotonous key.' While he grew out of this (apart, apparently, from when 'ironically assumed'), his relative frugality, preferring the third-class railway carriage to the first, and a tendency to lose himself in thought while at the dinner table would remain with him for life.

The experimental side of the course at Edinburgh was limited and sometimes verged on the amateurish. Maxwell noted in a letter to his friend Lewis Campbell:

> On Saturday, the natural philosophers ran up Arthur's Seat with the barometer. The Professor [presumably Forbes] set it up at the top and let us pant at it till it ran down with drops. He did not set it straight, and made the hill grow fifty feet; but we got it down again.

The barometer in question was likely to be an inverted tube of mercury, measuring atmospheric pressure which was then used to calculate the height above sea level of the famous rocky outcrop above Edinburgh.

In the same letter, Maxwell makes a first mention of a devil that would be a companion for much of his life – though not the titular demon of this book. He wrote:

> Then a game of the Devil, of whom there is a duality and a quaternity of sticks, so that I can play either conjunctly or severally. I can jump over him and bring him round without leaving go of the sticks, I can also keep him up behind me.

This refers to the game known as 'the devil on two sticks', now more commonly called diabolo, where a double cone, joined point to point, is kept in the air using a string between two rods.

For much of his career, Maxwell would supplement his academic work with experiments in a series of home laboratories that would eventually have been better equipped than a university. It was not until he was involved in setting up the prestigious Cavendish Laboratory in Cambridge (see Chapter 8) that he would have significant access to a professional, university-based workshop. During his time at Edinburgh University, he got together a small lab at Glenlair in a room over the wash-house. In the summer of 1848 (when Maxwell was seventeen), he wrote to Lewis Campbell:

> I have regularly set up shop now above the wash-house at the gate, in a garret. I have an old door set on two barrels, and two chairs, one of which is safe, and a skylight above, which will slide up and down.
>
> On the door (or table), there is [*sic*] a lot of bowls, jugs, plates, jam pigs,[¶¶] etc., containing water, salt, soda, sulphuric acid, blue vitriol,[‖‖] plumbago ore;[***] also broken glass, iron and copper wire, copper and zinc plate, bees' wax, sealing wax, clay, rosin, charcoal, a lens, a Smee's Galvanic apparatus,[†††] and a countless variety of little beetles, spiders, and wood lice, which fall into the different liquids and poison themselves … I am making copper seals with the device of a beetle. First, I thought a beetle was a good conductor, so I embedded one in wax (not at all cruel, because I slew him in boiling water in which he never kicked), leaving his back out, but he would not do.

Although Maxwell was busy with his experiments that summer, it didn't stop him from writing highly mathematical papers. He had continued to do this since his first success at the Royal Society of Edinburgh aged fourteen, though often the documents were just handwritten for the consumption of his friends. However, in 1848 he wrote a paper stretching to 22 long pages called 'On the Theory of Rolling Curves', published the following year in the *Transactions of the Royal Society of Edinburgh.* This combines geometry with some sophisticated algebra and calculus, describing how one curve, rolling along another curve (which is ‘fixed to the paper’) would produce a third curve.

Quoted in the biography by Campbell and Garnett, Maxwell remarks that his decision to switch from a legal track was made to pursue ‘another kind of laws’. Most undergraduates content themselves with the work programme that the university sets, but Maxwell was already at his best when exploring on his own, continuing his early experiments with some remarkably sophisticated developments – something that comes across particularly in his work on stress and polarised light.

A particular light

Maxwell had been introduced to the topic of polarisation – a variation in the direction of oscillation of waves of light, which can be separated by special materials – while still at school. His mother’s older brother, John Cay, took Maxwell and Lewis Campbell to visit the optical expert William Nicol, who had found a way to produce polarised light at will.

The concept of polarisation dated back to 1669, when Danish natural philosopher Erasmus Bartholin had been the first to explain the workings of an odd crystal known as Iceland spar. This is a form of calcite – crystalline calcium carbonate. If you put a chunk of the transparent crystal on top of, say, a document, you see not one, but two copies of the writing, shifted with respect to each other. The phenomenon itself had been known for centuries – it has even been suggested that the Vikings may have used ‘sunstones’ with a piece of Iceland spar in them as a navigating device to estimate distances. But Bartholin’s insight was to realise that the crystal split two different forms of light that were both present in ordinary sunlight.

When at the start of the nineteenth century Thomas Young demonstrated that light was a wave that rippled from side to side as it moved forward (known as a lateral or transverse wave), the French physicist Augustin Fresnel realised that this provided an explanation for the special ability of Iceland spar. Light waves from a source such as the Sun would be oriented in all directions – some would be rippling side to side while others oscillated up and down – in fact the waving could take place in any direction at right angles to the direction of the light beam's travel. If the crystal split apart waves rippling in different directions – the direction of the side-to-side ripple being described as its direction of polarisation – then the two images could be the result of the crystal separating rays with two different directions of polarisation.

When Maxwell's uncle John Cay took him and his friend to visit William Nicol, they were shown prisms made from Iceland spar which had the effect of splitting off just one polarisation of light (for a time these optical devices were known as nicols, after their maker). This seems to have inspired Maxwell while he was at Edinburgh University, with polarised light soon becoming the prime focus of his spare-time experiments. It was known that when such light is passed through ordinary glass there is relatively little effect. However, if the same light is shone through unannealed glass, glass that has been heated until it is glowing and then cooled very quickly, the polarised light produces a coloured pattern, caused by the internal stresses in the glass.

Initially, Maxwell experimented with pieces of window glass, heating them to red heat then rapidly cooling them.[‡‡‡] In a letter to Lewis Campbell he wrote:

> I cut out triangles, squares, etc., with a diamond, about 8 or 9 of a kind, and take them to the kitchen, and put them on a piece of iron in the fire one by one. When the bit is red hot, I drop it into a plate of iron sparks [filings] to cool, and so on till all are done.

To produce polarised light, he made his own polarisers using a matchbox with pieces of glass set in it to produce reflections (reflected light is partially polarised); he also attempted to make polarisers from crystalline saltpetre (potassium nitrate). Maxwell made watercolour paintings of the brightly coloured patterns that he obtained in his heated and cooled window glass, some of which he sent to William Nicol, who was sufficiently impressed to send Maxwell a pair of his optically precise nicols, producing far better polarised light than Maxwell had been able to obtain with his do-it-yourself matchbox devices.

From an engineering viewpoint, getting an understanding of the stresses inside an object is essential to predict how it will stand up to strain when it is put in use. Maxwell had the insight to see that if, for example, a girder could be made of a transparent material, it would be possible to use polarised light to study the internal stresses as the girder begins to bear a load. Clearly this isn't possible using an actual iron or steel girder – but if a model of it could be constructed in a suitable transparent material, it could be used to discover how stresses form in the structure and change under load, reducing the risk of structural collapse.

Unfortunately, glass doesn't respond well to strain, and the clear plastics and resins that would later be used in this 'photoelastic' method that Maxwell devised, and which is still used by engineers, weren't available at the time. Instead, with that same make-do-and-mend approach that had seen him attempt to use beetles as part of his electrical toolkit, he got hold of some gelatine from the Glenlair kitchen and used it to make clear jelly shapes. Maxwell was delighted to discover that his jellified models produced exactly the kinds of stress patterns he hoped for as he put them under strain.

The path to Cambridge

When not doing experiments, Maxwell would be working through numerous physical propositions or 'props' as he and his friends called them, often studying the most mundane of objects and trying to deduce something interesting from them. Sometimes these can seem a little bizarre. For example, in a letter written from Glenlair in October 1849 he noted: 'I have got an observation of the latitude just now with a saucer of treacle, but it is very windy.'

As well as more practical work, Maxwell followed up his pin and string mathematical paper and other topics while still an undergraduate. His most outstanding attempt of the period was to derive a mathematical analysis of the stress patterns he had observed using his photoelastic technique. He confirmed these mathematical formulae, covering different basic 3D shapes such as cylinders and beams, as much as he was able with his experimental work. This was a remarkable achievement for someone with his very limited experience, but he was to discover that it wasn't enough to perform careful experiments or to produce mathematics that successfully described them. It was also important that you could communicate your scientific findings effectively. He wrote up his work and asked Professor Forbes to present it to the Royal Society of Edinburgh.

Forbes may have been highly impressed with the younger Maxwell's ventures into mathematics, but this new paper was more directly impinging on his own field, and Maxwell was now nearing adulthood. Forbes did not think much of his writing style in the paper, which was refereed by Maxwell's mathematics lecturer, Philip Kelland. Forbes commented that Professor Kelland 'complains of the great obscurity of several parts owing to the abrupt transitions and want of distinction between what is assumed and what is proved in various passages'.

Professor Forbes went on to say: 'it must be useless to publish a paper for the use of scientific readers generally, the steps of which cannot, in many places, be followed by so expert an algebraist as Prof. Kelland; – if, indeed, they be *steps* at all …' This kind of criticism could have been deadly for a beginner who took it personally, but it spurred Maxwell into studying the best of the period's scientific writing, analysing the wording and structure to see what made it effective and incorporating what he discovered into his own style. While he never became one of the greats of science communication, after this his papers were usually lucid and well written.

There was something about Maxwell's personality that made him able to adapt well to constructive criticism in this way. He seems to have had the ideal balance of freedom to experiment and try things out, with a network of peers who were prepared to point out his failings and help him overcome them. Like his scientific hero Michael Faraday, Maxwell never gave himself the airs and graces of some of their contemporaries such as Sir Humphry Davy in London or, in later years, Maxwell's regular correspondent William Thomson, who would become Sir William and then Lord Kelvin. Maxwell's religious upbringing, his mixing with the country children on the estate and his down-to-earth humour seem to have protected him from ever having an over-inflated sense of his own importance.

Maxwell's paper on the mathematics of the stresses observed in his photoelastic experiments was originally submitted to Professor Forbes in December 1849. After Forbes and Kelland's feedback, Maxwell redrafted it in the spring of 1850 and the revised version, which had large chunks of the original omitted or reworded, appeared in the *Transactions of the Royal Society of Edinburgh* that year. It was a long piece of work running to 43 pages, which combined some of his own experimental observations with a much wider mathematical analysis.

Although Edinburgh allowed Maxwell considerable freedom in pushing forward his scientific thinking, it was still primarily seen as a track for him to achieve a degree on the way to a career in law. But as he wrote to Lewis Campbell on 22 March 1850:

> I have notions of reading the whole of *Corpus Juris* and Pandects [for his studies of law] in no time at all; but these are getting somewhat dim, as the Cambridge scheme has been howked up from its repose in the regions of abortions, and is as far forward as an inspection of the Cambridge *Calendar* and a communication with Cantabs.[§§§]

Maxwell decided that after three years at Edinburgh University, before he had completed his degree, he needed a more thorough scientific and mathematical content to his studies and applied to Peterhouse college, Cambridge, where his friend Peter Tait was already resident. Such a move was not uncommon. Tait had left Edinburgh for Cambridge after just one year and another friend, Allan Stewart, after two years. This change of academic venue required Maxwell's father's support, which seems to have been given wholeheartedly. John Clerk Maxwell travelled down to Cambridge with his son on 18 October 1850, as the young scientist started on the next leg of his academic journey.

Notes

1 – The description of travel to the Maxwell estate is from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 26.

2 – The idea that Maxwell's father undertook scientific experiments is from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 4.

3 – John Clerk Maxwell's paper 'Outline of a plan for combining machinery with the manual printing-press' was published in *The Edinburgh New Philosophical Journal,* 10 (1831): 352–7.

4 – The assertion that the family of Mary Godwin (Shelley) was of 'a very restricted income' despite having a governess is from Kathryn Harkup, *Making the Monster* (London: Bloomsbury Sigma, 2018), p. 11.

5 – The ill treatment of Maxwell by his tutor is recorded in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 43.

6 – Maxwell's early questions about how things worked are recorded in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 12.

7 – Maxwell's arriving back with his tunic in rags after his first day is described in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 50.

8 – Descriptions of contemporary English public schools and their limited curricula are from David Turner, *BBC History,* 'Georgian and Victorian public schools: Schools of hard knocks', June 2015, available at https://www.historyextra.com/period/georgian/georgian-and-victorian-public-schools-schools-of-hard-knocks/

9 – Baden Powell's concern that the higher classes were not gaining scientific knowledge is quoted in Pietro Corsi, *Science and Religion: Baden Powell and the Anglican Debate, 1800–1860* (Cambridge: Cambridge University Press, 1988), p. 116.

10 – Maxwell's first paper at the age of fourteen is in *Proceedings of the Royal Society of Edinburgh,* Vol. 2 (April 1846) and reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990) pp. 35–42.

11 – The description of Maxwell's holiday activities at Glenlair is from Peter Tait, 'James Clerk Maxwell: Obituary', *Proceedings of the Royal Society of Edinburgh,* Vol. 10 (1878–80): 331–9.

12 – Maxwell's letter to Lewis Campbell detailing his day at university, written from 31 Heriot Row, Edinburgh in November 1847 is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990). p. 69.

13 – Maxwell's maintenance of some odd behaviour at Edinburgh University is described in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 105.

14 – Maxwell's letter to Lewis Campbell on both the barometer experiment and the devil with two sticks, written from Glenlair on 26 April 1848, is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 116.

15 – Maxwell's letter to Lewis Campbell about his home lab, written on 5 July 1848, is in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 71.

16 – The paper 'On the Theory of Rolling Curves' was published in the *Trans. Roy. Soc. Edinb.,* 16 (1849): 519–40 and is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), pp. 74–95.

17 – Maxwell's change of subject to pursue 'another kind of laws' is noted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 131.

18 – Maxwell's description of heating shapes of window glass is from a letter to Lewis Campbell, written from Glenlair on 22 September 1848, reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), pp. 96–8.

19 – Maxwell's use of a saucer of treacle to 'observe the latitude' is mentioned in a letter to Lewis Campbell, quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 126.

20 – Forbes' criticism of Maxwell's writing style is quoted in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 186.

21 – The draft with revisions of Maxwell's paper 'On the Equilibrium of Elastic Solids' is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), pp. 133–83.

22 – Maxwell's change of plans from law is from a letter to Lewis Campbell quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 130.

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[*] It's the demon here – I'll be handling the footnotes throughout the book. There is something decidedly demonic about footnotes. For those of you not familiar with the English system of titles, a baronet is the only hereditary title that does not make someone a lord – they're a knight. If buying one sounds a little cheesy, bear in mind the whole idea was dreamed up by James I as a fundraiser.

[†] Penicuik House has been a shell since being destroyed by fire in 1899, but it was partly restored around 2014 and is now open to visitors.

[‡] Strictly speaking, the Victorian era didn't begin until Maxwell was six, but I am inclined to allow the author some leeway here.

[§] In other words, 'What makes it go?'

[¶] Maxwell was not the first great physicist to be brought up in a house with airs and graces beyond its physical reality. Newton's childhood home, the impressive-sounding Woolsthorpe Manor, was equally nothing more than a large farmhouse. It's interesting to speculate whether the hands-on life of a farm provides an ideal encouragement to take an interest in the world around us.

[||] Unlike the other houses Maxwell lived in throughout his working life, most of which remain in good condition, Glenlair is mostly a ruin since a fire in the 1920s, though the oldest part of the house remained habitable and was renovated in the 1990s.

[**] This was a distinctly trendy simile from Maxwell's contemporary at the Edinburgh Academy – Maxwell started school in 1842, only twelve years after the world's first steam railway, the Liverpool and Manchester, was opened. Presumably, the railway then had the same fascination for schoolchildren as space travel has more recently.

[††] Natural Philosophy was the generic term for science until the nineteenth century, as science originally simply meant a topic of knowledge – so, for instance, the favourite subject of us demons, theology, was known as the 'queen of the sciences'. A practitioner of what we would now call science was known as a natural philosopher. As philosophy became an increasingly specific discipline, the label changed to natural sciences, a term still used by some of the older universities.

[‡‡] There were none of your lazy internet searches back then, of course; this was a matter of physically sorting through books and journals. It's worth thinking that without Maxwell's work, we might not even have the internet today.

[§§] This is typical of the humour of Maxwell's circle: 'rude' here means 'rough and ready', but is used to get in a sly reference to Shakespeare, who has Puck speak of 'rude mechanicals' in *A Midsummer Night's Dream.*

[¶¶] Not as exciting as it sounds: nothing more exotic than jam jars.

[||||] The bright blue chemical compound, copper sulfate.

[***] Confusingly, since the name is reminiscent of the Latin for lead (*plumbum*), plumbago is in fact naturally occurring carbon – graphite. The ore was frequently confused for lead ore or galena as both are found as shiny black deposits – hence the way we still refer to the graphite in a pencil as its lead.

[†††] Surely the highlight of Maxwell's equipment, this was an impressive mahogany-framed six-cell battery retailing at an expensive £3 10 shillings. The advertising for the apparatus claimed that it would 'heat to redness 4 inches of platinum wire, fuse iron wire with

facility, and empower a sufficiently strong electro-magnet to sustain many hundredweights’.

[‡‡‡] Not to be tried at home as the glass may well shatter. As was not unusual at the time, Maxwell seems to have had little concern for personal health and safety.

[§§§] I.e. the University of Cambridge, traditionally given the abbreviation ‘Cantab’ from Universitas Cantabrigiensis, its Latin name.

Demonic Interlude II

In which electricity meets magnetism

With my creator safely set off on his way to Cambridge, this is a good opportunity to give you a little background on a topic that would come to dominate much of Jimmy's[*] life – electromagnetism. While inevitably from my own viewpoint it's JCM's interest in thermodynamics and the related field of statistical mechanics that makes him of particular value, a truly objective observer[†] would probably have to assess his contributions to electromagnetism as having the greater impact on the world.

Both electricity and magnetism were known as strange natural phenomena long before there was any idea of what might be going on, each considered totally separate from the other.[‡] We can get an idea of where the concept of electricity originated from its name. Both 'electricity' and 'electron' are derived from *electrum,* the Latin for amber (a name itself derived from a similar Greek word).

Natural electricity

When amber is rubbed, it generates static electricity in the same way that a balloon gets charged up when it is rubbed on your hair. This so-called triboelectric effect involves electrons coming loose as a result of the rubbing process, leaving the object rubbed and what it's rubbed with each having the opposite electrical charge. Electrical attraction means the balloon can then pick up very light objects through an induced charge and it can even produce a tiny spark. Induction comes into the electrical business quite frequently – it simply means that if you bring something that's electrically charged near an object it will tend to repel particles with the same charge in that object, so that the nearest side of the object has an opposite electrical charge, making the object – in this case, perhaps, a small piece of paper – attracted to the original source.

The triboelectric effect is probably also the mechanism responsible on a much larger scale for the charge build-up in the most dramatic natural example of electricity, a bolt of lightning. It’s worth spending a little time on lightning to get a feel for the early impression of electricity.

Lightning was surely the first observed electrical phenomenon, though initially its sheer magnitude resulted in it being labelled the work of an irritable god. Thanks to big-budget superhero movies, probably the best-known thunder god these days is the relative latecomer, the Norse god Thor; though earlier, the power of lightning-throwing was thought to be held by Zeus for the Greeks, Jupiter for the Romans, and Indra in the Hindu pantheon. No doubt there have been many more. When gods weren’t blamed, lightning, like other strange appearances in the sky such as comets and red moons, was considered to be a warning of dire events to come. In the first century AD, for example, Pliny the Elder said that a thunderstorm was prophetic, direful and cursed.

The superstitious view of lightning is hardly surprising. It’s the most dramatic natural phenomenon that the majority of people will experience – certainly the most common of nature’s big beasts, with at any one time typically around 1,800 thunderstorms active around the world. And lightning doesn’t just look and sound impressive, it has the capability to blast trees and to kill.

One common myth associated with lightning is that it does not strike the same place twice. Some rural areas of Britain used to have a brisk trade in what were known as thunderstones. These were stones that had a hole in the middle, which were bought as a safeguard to place up the chimney of a house. The idea was that the thunderstone had already been struck by lightning, which was thought to have caused the hole, so lightning would be unable to hit the chimney without breaking the ‘striking the same place twice’ rule.

Unfortunately, there are two problems with this folk remedy. One is that lightning is entirely happy to strike the same place twice and quite often does so. If a location is susceptible to lightning strikes, it’s not unusual for it to get several hits in one day. The Empire State Building, for instance, has received as many as fifteen strikes in a single storm. When you think about it, lightning would have to be conscious and directed if it never returned to the same spot.

Perhaps the most impressive example of multiple strikes, though, was not on a building but on the US park ranger Roy Sullivan, who entered the *Guinness Book of Records* as the person who had been hit by lightning the most times – a total of seven strikes, all of which he survived. The other problem with using thunderstones to ward off lightning is that these unusual formations weren't caused by lightning at all – they are the remains of Stone Age hammers where a wooden handle and leather bindings have long ago rotted away.

In general demonic use (and we use them a lot), thunder and lightning are pretty much interchangeable because we now know that thunder is simply the noise produced by the lightning bolt ripping open the air – traditionally they were considered linked but independent events because of the variable time difference between them. This reflects light's immense speed of 299,792,458 metres per second compared with sound's plodding 343 metres per second at sea level.

It's hard to imagine that something as dramatic as a lightning bolt could be down to a similar procedure to rubbing a balloon on your hair – and, to be honest, the means of lightning production isn't anything like certain – but the model that has been generally supported since the 1950s is a triboelectric mechanism. In a thundercloud there are particles of ice and supercooled water droplets as well as graupel (miniature hailstones), all churning and jostling about in the clouds as warmer and cooler air streams collide. This is thought to result in the heavier graupel getting a relative negative charge. The charge becomes separated as the graupel sink towards the bottom of the cloud while the lighter, positively charged particles rise. This conveyor-like process is thought to occur many times, gradually building up a bigger and bigger electrical potential difference.

It has been suggested by some scientists that cosmic rays could also have a role to play in triggering lightning. Cosmic rays are streams of high-energy charged particles that come rocketing towards the Earth, but that are mostly fended off by the planet's magnetic field and the atmosphere. Russian researchers have suggested that cosmic rays could produce a stream of electrons that build up in a chain reaction as the ice particles circulate. However, other scientists consider this mechanism highly doubtful.

From the skies to the laboratory

What we do know for certain, though, is that lightning is nothing more than an electrical discharge like that produced by rubbing a balloon – though admittedly a discharge with a remarkable kick. The eighteenth-century American journalist, diplomat and scientist Benjamin Franklin is famous for demonstrating this by flying a kite in a thunderstorm with a key attached to the kite string. Or rather he certainly described the experiment in 1750 – it's quite possible, though, that he had someone else carry out the risky procedure.

It's very unlikely that Franklin (or whoever he persuaded to take the risk) flew a kite and waited for it to be struck by lightning, as the legendary experiment is often portrayed. Instead, his proposal was to tap into the electrical charge in the thunderclouds to cause a build-up of electricity on the key by induction, with no lightning strike taking place. The charge from the key was then passed to a Leiden jar, an early method of storing electricity, where it could be demonstrated that the electricity from storm clouds was just the same as the tamer-seeming ground-based variety.

There's no doubt that some people have attempted the experiment Franklin described, but it is phenomenally dangerous. Just consider the amount of energy in a typical lightning flash – perhaps half a billion joules. It takes 10 joules to run a 10-watt bulb for a second. The amount of energy in a lightning bolt is more like the output of a mid-sized power station for a second. The electrical current rips through the air, heating it suddenly and causing the rumble of thunder. The temperature in a bolt peaks at around 20,000–30,000°C, as much as five times the surface temperature of the Sun.[§]

You can't see electricity itself in a lightning bolt. It is atoms that have received energy from the lightning which blast out light as their electrons are boosted in energy then fall back to their usual levels. And what's produced is the full spectrum of electromagnetic radiation, all the way from radio waves up to X-rays and gamma rays. We don't expect electricity to be able to flow through the air because our atmosphere is quite a good insulator. It takes around 30,000 volts to get a spark to jump across just one centimetre at normal levels of humidity (the damper the air, the easier it is for electricity to flow).

It seems reasonable that dampness helps because we are used to water being seen as a good conductor of electricity (which is why it's not a good idea to get electrical equipment wet). Oddly, though, like air, water is actually a reasonably good insulator. Take absolutely pure water and it hardly conducts at all. But it almost always contains the ions of substances that are dissolved in it, and these carry the current. Ions (electrically charged atoms) are also responsible for carrying the electricity through the air in lightning, but to produce the vast streamers of electric discharge in a bolt of lightning still takes a huge amount of electrical power.

Once a significant secondary charge has been induced, something weird happens. There is a relatively weak flow of electricity between the negative storm cloud and its positive target. This flow of electricity ionises the air. Just as in water, a collection of ions in the air conducts electricity much better than a collection of neutral atoms. This weak discharge from the cloud, called a leader, sets up a path for the main burst of lightning, the return stroke, which goes in the opposite direction – in the case of a ground strike, the main stroke runs from the ground up to the cloud rather than in the obvious direction.

Whether or not Benjamin Franklin took a kite out in a thunderstorm, he certainly did invent the lightning rod (also known as a lightning conductor). The idea of this simple device is to provide a metal spike on the highest part of a building, connected via a thick metal conductor to the ground. This spike is most likely to receive a hit and was intended to conduct the electricity away, reducing damage to the structure. In practice more often than not the lightning rod prevents a lightning strike from ever happening. The rod allows any charge being induced around the spike to leak away to the ground, reducing the chances of a leader forming.

Lightning gives a dramatic natural example of electricity in action, but it's difficult to study because it does not take place in a controlled environment. By the eighteenth century, static electricity was being used in dramatic demonstrations such as the 'electric boy', where a youth was suspended from ribbons and charged up by rubbing glass rods with silk. He would then be used to give the audience shocks and to attract light objects. However, it would be the nineteenth century before usable current electricity, where electrical charges flow through wires, became viable. Before we get on to that, we need to take a step back and bring magnetism alongside its electrical cousin.

Magnetic matter

Magnets have been known since ancient times in the form of naturally occurring lodestones. These are chunks of the mineral magnetite – an oxide of iron. Most magnetite has no special properties, but when it carries certain impurities it has the right structure to become a permanent magnet. It's not 100 per cent certain how the lodestones became magnetised in the first place – the most obvious suspect, the Earth's magnetic field, is far too weak. It is suspected, particularly as lodestones only tend to be found near the surface of the Earth, that they were magnetised by lightning strikes (so, in effect, lodestones are the true thunderstones). With the kind of symmetry we demons prefer to avoid – as humans find it far too attractive – once we've united electricity and magnetism, each is capable of producing the other.

The earliest recorded attempt to take a scientific approach to magnetism came from a thirteenth-century French scholar named Peter de Maricourt, though better known as Peter Peregrinus ('Peregrinus' usually referred to a stranger or foreigner – the implication is that he was a wanderer or pilgrim who didn't stay long at a single institution). We know little of Peter himself, though there was a village called Mehariscourt, near the abbey of Corbie in Picardy, the French region that he is associated with in legend. The thirteenth-century English natural philosopher and friar Roger Bacon said of Peter, whom he had met in Paris:

> He gains knowledge of matters of nature, medicine and alchemy through experiment, and all that is in the heaven and in the earth beneath. He is ashamed if any old woman or soldier or countryman knows about something he does not know about the country. So he has pried into the work of metal-founders and what is wrought in gold and silver and other metals and all minerals …
>
> So without him philosophy cannot be completed, nor yet handled with advantage and certainty. But just as he is too worthy for any reward, so he does not seek one for himself. For if he wished to dwell with kings and princes, he could easily find those who would honour and enrich him. Or if in Paris he were to display his knowledge through the works of wisdom, the whole world would follow him. But because in both these ways he would be hindered from the bulk of the experiments in which lie his chief delight, he neglects all honours and riches, especially since he will be able, when he wishes, to reach riches by his own wisdom.

In 1269 Peter completed his *Epistola de Magnete,* a detailed letter which describes the two differing poles of a magnet, attraction and repulsion, how to magnetise iron with a lodestone, and the Earth's magnetism. He also gives some details on constructing compasses, both by the then common approach of floating a magnet on water and by using the more advanced approach of mounting a thin magnet on a pivot. Peter's work describes practical applications rather than providing any theoretical basis, but it was the definitive document on the subject through to the start of the seventeenth century. Then, Peter's work was eclipsed by that of the English natural philosopher William Gilbert.

Gilbert's book, *De Magnete,* went into far more detail than Peter had been able to in his letter, and gave far greater consideration to how the Earth itself could act as a huge magnet. To explore the way that such a magnet would behave, Gilbert constructed spherical metal magnets known as terrella. These helped him understand the property of dip, where a compass needle does not point horizontally due to its position on the Earth's surface.

Inevitably Gilbert did not get everything right. His biggest error was suggesting that gravity was the same as magnetism, though the similarity of principle was a good observation. But his book, which also covered some aspects of static electricity, restarted the interest in thinking about the nature of magnetism over and above its usefulness for constructing compasses.

The birth of electromagnetism

We're now well placed to move on to the discovery of current electricity – electricity that flows from place to place – thanks to Italian physicist Alessandro Volta's 1799 electrical pile (a collection of which was called a battery), and the Danish Hans Christian Oersted's 1820 discovery that electrical currents produce a magnetic effect.

These were precursors to the remarkable work on electricity and magnetism that Michael Faraday would do. Faraday realised that the two were strongly interconnected and made popular the term 'electromagnetism', devised for their combined study by Oersted (though Faraday wrote it, as would be common initially in English, as electromagnetism). Faraday's discoveries proved essential for the work that JCM would carry out.

Because of Faraday's importance to the development of JCM's thinking, his role needs exploring further. Faraday's family had come to London from Westmorland, in the English Lake District, before he was born in search of work for his blacksmith father. In 1805, at the age of fourteen, Faraday was apprenticed to bookbinder George Riebau, a refugee from the French revolution. Faraday spent all his spare time in the shop, teaching himself from the books that were in to be bound. These heavy volumes, along with the lectures provided by a self-improvement group, the City Philosophical Society, gave Faraday a single-minded intent to break into the closed world of science.

One of Riebau's clients, a Mr Dance, got Faraday a temporary job assisting the Royal Institution's star scientist, Humphry Davy, while Davy's usual assistant was injured. The Institution was a relatively new organisation, established in 1799 by leading British natural philosophers as a means to spread the word about science to the wider population and to provide facilities for undertaking research. Working with Davy was a dream opportunity for Faraday, but he was soon sent back to the bookbinders. Faraday kept up a steady barrage of applications for jobs in scientific establishments. Eventually, in 1813, he got the permanent post of lab assistant at the Royal Institution.

By 1821, with a promotion under his belt, the young scientist was making steady, if unremarkable progress. He was asked to write an article summarising the latest position on electromagnetism, the emerging field of the interaction between electricity and magnetism. To help do so, Faraday replicated the experiments he had read about. As he passed electricity down a wire running alongside a fixed magnet, he saw something that first puzzled him, then challenged his imagination. When the current flowed, the wire moved, circling round the magnet. As far as he could tell, this was a new discovery, and he realised that it needed publication. He wrote it up with little consultation with his peers and was promptly accused of plagiarism.

The man Faraday was supposed to have stolen the idea from was William Wollaston, one of the scientists whose work Faraday had included in his review. Wollaston had started out as a doctor, but had given up medicine as his eyesight was failing. He had decided (with limited evidence) that electricity spiralled its way along wires like a corkscrew. Wollaston had asked his friend Sir Humphry Davy to search for any evidence of this motion. Davy was unable to do so. However, despite a very limited connection, other than electricity and rotation, between Wollaston's theory and Faraday's experiment, Wollaston was convinced that Faraday had stolen his idea. This appalled Faraday. He asked his mentor Davy to help, but to no avail.

While Davy was willing to accept that Faraday did good work, they were miles apart in social status. Davy was a society darling who regularly met with royalty. Early in his career, Faraday had accompanied Davy and the new Mrs Davy on a trip around European scientific establishments. Rather than treat Faraday as an equal, the Davys expected him to take on the role of valet as well as scientific assistant. As far as Davy was concerned, Wollaston, a professional man, was far more of a social equal. He took Wollaston's side. This was the end of anything more than a purely professional relationship between Faraday and Davy.

Luckily, Davy's influence was not sufficient to persuade others that Faraday had copied Wollaston's ideas. And the steady rotation of the wire around the magnet was more than a pretty demonstration: it formed the basis of the electric motor. Faraday had moved out from under Davy's shadow. Two years later Faraday would be elected to a fellowship of the prestigious Royal Society with only one vote against him. That of Sir Humphry Davy.

It would be ten years before Faraday returned to electricity and magnetism. The pain of the accusations and Davy's betrayal bit deep. He turned his attention to chemistry and took on the administrative job of Director of the Royal Institution Laboratory, establishing the Friday Night Discourses and a series of Christmas events for children. But Faraday could not resist the challenge of electromagnetism for ever. By 1831 there was evidence that electricity flowing through a wire could generate a current in another, unconnected wire, somehow communicating across space.

This near-magical proposition – induction – was enough to restart Faraday's enthusiasm for electromagnetism. He constructed a pair of wire coils, wrapping each long, insulated piece of wire around the straight sides of an elongated hoop of iron. He expected to see a steady flow of electricity in the second coil, somehow leaking through to it via the metal hoop, when he powered up the first. Instead there was only a short flow of current in the second coil when the first coil was turned on or off, which soon disappeared.

How, then, was the first coil of wire managing to produce an effect in the second at a distance? As we have seen, Faraday's first investigation had included the way that a coil of electric wire could produce magnetism. And there was no doubt that magnets worked at a distance – a compass showed that to be the case. When the current flowed in the first wire, then, it would act as a magnet. Faraday realised that if the changing level of magnetism generated a new current in the second wire, rather than electricity leaking across the metal core, it would follow that only a short burst of current would be induced in that second wire. He was soon able to demonstrate the generation of electricity by moving a permanent magnet through a coil, devising a basic electrical generator.

The linkage Faraday demonstrated between electricity and magnetism was difficult for scientists to explain. It was known that when iron filings were sprinkled on a sheet of paper and held above a magnet, the tiny pieces of metal would pull together into curved lines that provided a map of the magnet's invisible power. With his limited mathematical ability, Faraday was unable to provide equations to describe the effect; instead he imagined the results he had observed in terms of these lines, which he called 'lines of force'. If he moved a wire near the magnet, the wire was repeatedly cutting through the lines of force, one after another. Each interaction with these imagined lines in apparently empty space generated a flow of electrical current through the wire.

With this picture in mind, Faraday could reconstruct why the electrical induction occurred the way it did. Before the first electrical coil was switched on, the lines of force did not emerge from the coil. But when he started the current flowing, turning the coil into a magnet, the lines moved out into place like the ribs of an opening umbrella. As the lines of force moved out, they cut through the wire of the second coil, one after the other. The way the current pulsed briefly when the magnet was switched on meant that the lines of force did not appear instantly in place when he switched on the magnetic coil; they gradually moved out into position, otherwise the second coil wouldn't interact with the lines and generate a current. Something was travelling through the air, an invisible magnetic phenomenon.

A matter of speculation

Faraday’s lines of force were visionary, but initially he was wary about revealing their full implications. He could not have forgotten what had happened when Davy had abandoned him. Instead of publishing all his results, he hid his most controversial ideas away in a sealed envelope, dated 12 March 1832, intending it to be opened after his death. And this document went one step further, giving a hint of something JCM would eventually make his own. In Faraday’s mental model, the lines of force moved outwards from the electromagnet when he switched it on. But what exactly did he think was moving? Faraday wrote:

> I am inclined to compare the diffusion of magnetic forces from a magnetic pole, to the vibrations upon the surface of disturbed water, or those of air in the phenomena of sound: i.e. I am inclined to think the vibratory theory will apply to these phenomena, as it does to sound, and most probably to light.

This inspired linkage of magnetic vibrations – waves – and the nature of light stayed in the safe inside its sealed envelope until just before nine o’clock on the evening of Friday, 10 April 1846, when legend has it Charles Wheatstone, due to give a lecture on his electro-magnetic chronoscope,[¶] panicked and ran out. His friend, Faraday, is said to have presented Wheatstone’s brief talk, then, without time for preparation, is supposed to have given the most inspired lecture of his career: a first insight into the inseparable nature of light, electricity and magnetism.

In reality, the Royal Institution’s records show that on that evening Faraday substituted for another scientist, James Napier, who had given a week’s notice of his absence. It is certainly true, though, that Faraday spoke about Wheatstone’s delightfully named but wholly forgettable electro-magnetic chronoscope. And then, when his colleague’s notes ran out, Faraday began to improvise.

He described light as a vibration, rippling through the invisible magnetic force lines that filled space. This was a remarkable insight to describe in that lecture theatre in 1846. The Royal Institution had moved to its newly-built home on Albemarle Street in London’s fashionable Mayfair. Faraday was positioned at the same polished wooden demonstrator’s bench that still stands in the imposing semi-circular theatre. This was before electric lighting, when the only sources of night-time illumination were oil lamps and candles and the flare of gas lights. To Faraday’s audience, electricity and magnetism were novelties, the inexplicable connection enabling machinery like the chronoscope. Faraday’s leap of genius, connecting the ethereal phenomenon of light with magnets and electrical coils, was inspired.

Faraday would later say that he ‘threw out as matter for speculation, the vague impressions of my mind’. But those impressions were the result of long thought and the outcome was remarkable. Faraday told his audience:

> The views which I am so bold as to put forth consider, there-fore, radiation as a high species of vibration in the lines of force which are known to connect particles, and also masses of matter, together. It endeavours to dismiss the aether,[‖] but not the vibrations.

As we have seen, unlike JCM, Faraday was no mathematician, yet he had produced a visionary idea of the nature of electricity and magnetism. He believed they produced a sphere of influence around themselves which he would call a ‘field’. Led in part by the way that iron filings line up to connect the two poles of a magnet, Faraday thought of his fields being made up of the lines of force that emanated from magnetic poles or electrical charges. When another electrical or magnetic object broke these lines of force they felt an influence. The field lines were envisaged in a way that tied in with many of the behaviours of electricity and magnetism. For example, when lines of force were compressed together, they repelled each other. And Faraday had also set the seeds of understanding the nature of light by making the remarkable leap from the familiar effects of electricity and magnetism to the concept of waves in a field of force.

All of this would be essential background when JCM began to consider the matter. Although Faraday is rightly celebrated for his contribution to the practical side of devising electric motors and generators, the approach he took theoretically was even more fundamental to the way that physics would develop. His concept of fields, considered by some of his contemporaries as hand-waving, vague nothings, would become the standard way that physicists looked at the world, and remains so to this day, often replacing more familiar models of waves or particles.

Those more mathematical contemporaries who criticised Faraday’s fields pointed out that their own approach, which considered electrical charges and magnetic poles as points that influenced other objects at a distance, obeying an inverse square law like gravity, produced numerical results that could be matched to experiment. However, the fields had a huge conceptual advantage. The point-based mathematical models depended on a mysterious influence at a distance. Just as Newton's gravitational theory did not explain how gravity worked across empty space (this would take Einstein's work), so electricity and magnetism could only be explained as causing strange actions at a distance. It was this that Newton's contemporaries mocked in his approach to gravity as being 'occult'.

Fields, on the other hand, did away with the need for action at a distance. An electrical charge, for example, acted on the field where it was situated, not on another charge at some distant place. That action then rippled through the field lines to reach the other location. But before the field concept could be considered an effective approach for physics, JCM would have to take Faraday's qualitative concept and turn it into a mathematical structure that would enable the workings of electromagnetism to be understood and harnessed.

That, though, is still a long way in the future in our story. With the basic ideas of electromagnetism firmly under our belts, let's rejoin the young Maxwell and his pater on the road to Cambridge.

Notes

1– Roger Bacon's praise for Peter Peregrinus is from Roger Bacon, *Opus Tertius,* quoted in Brian Clegg, *The First Scientist* (London: Constable & Robinson, 2003), p. 33.

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[*] To me, Maxwell will always be Jimmy or Jim, but the wording offends my editor, so henceforth I shall refer to him as JCM.

[†] Not a demon, then.

[‡] Bizarrely, you humans still teach your young children about electricity and magnetism separately. Sometimes I suspect that demons are responsible for your education system.

[§] Or 'nice and cosy' as we demons would say.

[¶] Not as impressive as it sounds: just an electrically controlled clock.

[||] The aether or ether was the imagined medium filling all space in which the waves of light were thought to be vibrations. Faraday thought that with fields in place, there was no need for its existence.

Chapter 2

A most original young man

On the way to Cambridge in 1850, Maxwell and his father had stopped off at two great cathedrals – Peterborough and Ely[*] – so the relatively small Peterhouse, to the south of the city centre where King's Parade becomes Trumpington Street, may have seemed far less of an architectural marvel. Yet the college should have been an ideal match for Maxwell on his first significant venture outside Scotland. Having his friends Tait and Stewart there to ease the way would have made the transition to Cambridge's social foibles – rather more sophisticated than Edinburgh at the time – easier to make. Because Peterhouse was one of the smaller colleges, it would have felt a less pressured environment than, say, Trinity or King's.

Maxwell was given rooms in college with plenty of natural light, something that suited his inclination to experiment – he had a sizeable collection from his home laboratory sent after him on the journey down to Cambridge.[†] The availability of good space at Peterhouse seems to have been one of his reasons for choosing the college. Mrs Morrison, the mother of Maxwell's friend Lewis Campbell, noted in her journal before Maxwell had chosen his college that Maxwell 'came in full of Forbes' recommendation of Trinity College above all others at Cambridge and that Peterhouse was less expensive than Caius; that the latter is too full to admit of rooms, and freshmen are obliged to lodge out.' Yet, within weeks of arriving in Cambridge, Maxwell was looking to move on.

Stepping up to Trinity

After a term at Peterhouse, Maxwell transferred to Trinity College – a relatively unusual step to take now, as teaching is largely provided by the university rather than the college. However, in Maxwell's day, the college you were a member of contributed significantly to the quality of the education you received. Far more direct teaching was provided by the college than is the case now, and some aspects of what was provided at Peterhouse were limited (despite having a good record in mathematics).

What's more, private tutors were then prevalent and could have a big influence on a student's success; it seemed that Maxwell wasn't getting on well with his tutor at Peterhouse. Maxwell's father had also found out that his son had little chance of remaining at Peterhouse after graduating. There would probably be only one fellowship available for Maxwell's year, in which it was clear he had several challengers. At the much larger Trinity College, the alma mater and firm favourite of family friend Professor Forbes, Maxwell would have a better chance of gaining a fellowship and staying on.

It's probably no coincidence that Maxwell was supported in the move to Trinity by James Forbes, who told the master of the college that 'he [Maxwell] is not a little uncouth in his manners, but withal one of the most original young men I have ever met with'. Not entirely surprisingly, given his background, at this stage in his life Maxwell was a strange mixture of wide-ranging information and a rambling lack of structure. Peter Tait commented that Maxwell had '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'.

Although Maxwell threw himself into the academic world and thrived at Cambridge, seeming to benefit particularly from the lively social life and intellectual cut-and-thrust that he experienced in Trinity College, he was determined to pack as much into his time there as he could. He had always been enthusiastic for exercise, but with his daily timetable already filled, for a period he devised a way to keep fit despite the restrictions that required students to remain in college at night time. A student with rooms on the same staircase as Maxwell remembered:

> From 2 to 2:30 a.m. he took exercise by running along the upper corridor, down the stairs, along the lower corridor, then up the stairs, and so on until the inhabitants of the rooms along his track got up and lay *perdus*[‡] behind their sporting-doors[§] to have shots at him with boots, hair brushes, etc., as he passed.

This timing was part of a set of experiments Maxwell undertook to determine the best possible hours for sleep and work – everything about life seems to have provided him with an opportunity for experiment. In

1851, for example, he noted in a letter that he had tried out sleeping after hall (the evening meal in the ornate college hall):

> I went to bed from 5 to 9.30, and read very hard from 10 to 2, and slept again from 2.30 to 7. I intend some time to try for a week together sleeping from 5 to 1, and reading the rest of the morning. This is practical scepticism with respect to early rising.

The results of his experiments were not published, but he seems finally to have settled for more sociable hours.

Becoming an Apostle

Clear evidence that Maxwell's air of a country bumpkin was wearing off came in his election to the Select Essay Club, better known by the nickname 'the Apostles', an elite intellectual club which, as the name suggests, originally had twelve members. It was a university-wide group, but drew largely on a group of wealthy colleges, including Trinity. The club would number the likes of Alfred Tennyson, Bertrand Russell and John Maynard Keynes among its members – and still exists. Unlike the infamous Oxford Bullingdon Club, the Apostles meetings were fixed around tea rather than alcohol-fuelled dining, and it had a far more intellectual basis, though it still suffered from some of the affectations of a secret society. It is highly unlikely that Maxwell would have been considered for such a club if he still came across as 'uncouth in his manners'.

It was perhaps due to a more sophisticated circle of friends that during his time at Cambridge, Maxwell made his only known foray into spiritualism, then at the height of its public interest. His friend Lewis Campbell notes that even the 'occult' sciences, in the then fashionable shapes of electro-biology and table-turning, received a share of Maxwell's 'ironical attention'. This was despite a dark warning from Maxwell's father who noted that an acquaintance had known 'two cases of nervous people whose minds were quite disordered' by electro-biology, and warned:

> I hope it is not in fashion at Cambridge, and at any rate that you do not meddle with it. If it does anything, it is more likely to be harm than good; and if harm ensues, the evil might be irreparable, so let me hear that you have dismissed it.

‘Electro-biology’ sounds like an early attempt at understanding the electrical aspect of the brain and nervous system, but was in reality an alternative term for animal magnetism. Both labels were attempts to give mesmerism (also known as hypnotism) a more scientific-sounding context. Electro-biology was particularly favoured as a term among stage hypnotists. Table-turning would have been considered even worse by Maxwell’s devout father. It was a form of séance where the table was lifted and moved as the participants sat around it, supposedly powered by spirit intervention, but more likely to be due to the practitioner’s use of his or her feet or hands.

It’s quite possible that Maxwell was put off further exploration by the fate of Michael Faraday, who experimented with table-turning and showed that the movement of the table was due to the pressure of participants’ fingers on it, quite possibly unconsciously making it move as they hoped. Faraday was then deluged with letters asking if he could explain various other phenomena as if, Maxwell noted, ‘Faraday had made a proclamation of Omniscience. Such is the fate of men who make real experiments in the popular occult sciences … Our anti-scientific men here triumph over Faraday.’ It’s likely Maxwell did not want to suffer a similar fate.

It was around this time that Lewis Campbell wrote a pen sketch of Maxwell that is interesting to set against the rather stern-looking portraits of the day. Campbell describes Maxwell as follows:

> His dark brown eye seems to have deepened, some parts of the iris being almost black … His hair and incipient beard were raven black, with a crisp strength in each particular hair, that gave him more the look of a Nazarite than of a nineteenth century youth. His dress was plain and neat, only remarkable for the absence of anything adventitious (starch, loose collar, studs, etc.), and an ‘aesthetic’ taste might have perceived in its sober hues the effect of his marvellous eye for harmony of colour.

Cats and rhymes

One thing that didn’t change for Maxwell while at Cambridge was his enthusiasm for animals. Many Cambridge colleges banned the keeping of dogs (and still do – the dog belonging to the current Master of Selwyn College is officially designated the college cat), which Maxwell would have found a wrench, but he made up for it by making friends with the cats that were employed to keep mice down in college. Being Maxwell, this led to an experiment which gained him a questionable reputation at the time, as he explained looking back in a letter to his wife Katherine written in 1870 when he was visiting Trinity College as an examiner for mathematics:

> There is a tradition in Trinity that when I was here I discovered a method of throwing a cat so as not to light on its feet, and that I used to throw cats out of windows. I had to explain that the proper object of the research was to find how quick the cat would turn round, and that the proper method was to let the cat drop on a table or bed from about two inches, and that even then the cat lights on her feet.

Maxwell also kept up a habit of writing verse while at Cambridge. This would be a pastime he indulged in throughout his life, covering the whole gamut from translations of classical poetry, through serious odes, love poems to his wife when later married, and ventures into comic verse. Sometimes his work would touch on very specific aspects of his work and experience, such as his Cambridge piece ‘Lines written under the conviction that it is not wise to read Mathematics in November after one’s fire is out’. The opening verses of another poem from his youthful Cambridge days, entitled ‘A Vision (of a Wrangler, of a University, of Pedantry and of Philosophy)’ illustrates Maxwell in full comic mode:

Deep St Mary’s bell had sounded,
And the twelve notes gently rounded
Endless chimneys that surrounded
My abode in Trinity.
(Letter G, Old Court, South Attics)
I shut up my mathematics,
That confounded hydrostatics –
Sink it in the deepest sea.

In the grate the flickering embers
Served to show how dull November’s
Fogs had stamped my torpid members,
Like a plucked and skinny goose.
And as I prepared for bed, I
Asked myself with voice unsteady,
If of all the stuff I read, I
Ever made the slightest use.

The Wranglers

At the time, all Cambridge students were required to take a series of mathematics papers in their finals. The basic exams, which could be passed by learning the fundamentals of the course, were relatively straightforward. But honours students took papers providing them with an extended set of problems over four days. The questions were deliberately obscure, requiring a different kind of thinking and taxing the students' reasoning skills to the limit. The scale of this undertaking can be seen from the details of the 1854 Tripos,[¶] where honours students took sixteen papers, comprising 44.5 hours of examination, working through 211 questions, while the best of the best went on to spend three more days on the 63 additional questions of the Smith's Prize papers.

Those who completed the whole of this gruelling mathematical challenge and came through with first-class honours were given the title 'Wrangler', their position in the listing as hard-fought as the 'Head of the River' in the rowing races. Achieving top position as 'Senior Wrangler' was widely regarded as the ultimate academic achievement in Britain and was feted far beyond Cambridge.

Maxwell achieved the position of Second Wrangler,[‖] and in the separate, even harder mathematical exams for the Smith's Prize was declared joint winner with Senior Wrangler Edward Routh, who would go on to be influential in the mathematics of moving bodies and would develop the beginnings of what became control systems theory.

It's arguable that Maxwell's mix of an Edinburgh and Cambridge education provided the perfect combination to break out of the approach to physics that was deeply embedded in academia at the time. Had he stayed in the Scottish system he would have been absorbed into a tradition that combined experiment with natural philosophy – but Cambridge gave him the extra abilities to take a more detailed mathematical approach, and the capacity to work with the rigour needed to move on to the next stage of the development of physics. Maxwell developed a working method that was a hybrid of the two traditions.

Maxwell's success in the mathematics exams and the Smith's Prize was exactly what he needed to ensure a continued place at the university, winning him the position of bachelor-scholar at Trinity with the near certainty of a fellowship to follow soon in the future. Now he had more time for his own projects. Continuing his fascination with light from his investigations of polarisations and the stress experiments, Maxwell found a new interest in the way that human beings perceive different colours.

Colour vision

At the time, doctors could do little more than peer at an open eye and hope to see into it, but Maxwell constructed one of the first ophthalmoscopes, in effect a microscope for examining the inner workings of the eye. With it, he subjected human and particularly dogs' eyes to lengthy study, and was able to reveal the network of blood vessels on the inner surface. He wrote to his aunt, Miss Cay, in Edinburgh in the spring of 1854:

> I have made an instrument for seeing into the eye through the pupil. The difficulty is to throw the light in at that small hole and look at it at the same time; but that difficulty is overcome, and I can see a large part of the back of the eye quite distinctly with the image of the candle on it. People find no inconvenience in being examined, and I have got dogs to sit quite still and keep their eyes steady. Dogs' eyes are very beautiful behind, a copper-coloured ground, with glorious bright patches and networks of blue, yellow and green, with blood-vessels great and small.

This work with his ophthalmoscope appealed to his continued interest in the detail of natural phenomena, but it gave no obvious clues as to the mechanism within the eye that enables us to distinguish between colours.

In working this out, Maxwell had two lines of enquiry. The better-established understanding at the time came from artists, who for centuries had been mixing different pigments to produce a palette of colours. The painters considered that red, yellow and blue were the 'primary' colours, able to produce any of the other colours when mixed together. The versatile English doctor and physicist Thomas Young had suggested that the eye worked in a similar fashion to the artist's palette, but in reverse. Different areas of the retina, Young believed, were sensitive to red, yellow and blue – or to be more precise, he suggested that each 'sensitive filament' of the optic nerve was split into three portions, one dealing with each of the primary colours, hence being able to construct the colour range that we see.

Maxwell was also aware of a strand of more physics-related experiments on light and colour from the natural sciences, which stretched back to Isaac Newton. It was while Newton was himself at Trinity College that he had performed his famous experiments. Piercing the blinds of his room, he had let a narrow beam of sunlight through and split it into the rainbow colours using a prism that he bought at a local fair.**

It was Newton who dreamed up red, orange, yellow, green, blue, indigo and violet as the colours of the rainbow. In reality, seven appears a strange number to have selected. There are far more colours if you examine a rainbow under the microscope, but to the naked eye there only appear to be six broad bands, merging Newton's three variants of blue into two. It's thought Newton went for the number seven so there would be the same number of rainbow colours as musical notes, an appeal to the harmony of nature. The ability of a prism to produce a rainbow was well known – that's why they were on sale at the fair as toys – but the prevailing theory at the time for why this happened was that the incoming white light was being coloured by impurities in the glass.

Newton's genius was to separate off individual colours from a prism's output and send them through a second prism. No individual colour was changed by passing through a second piece of glass – suggesting that the prism did not add the colour, but merely separated out the colours that were already present in the white light of the Sun. Newton confirmed this by focusing the rainbow colours with a lens and producing white light again. If these colours were all in white light, but when that light fell on, say, a red apple we see only red, it seemed reasonable that the apple was absorbing many of the colours in the spectrum while reflecting only the red.

Some colours that we can see, though, simply aren't present in a rainbow spectrum of light. Think of brown or magenta (cerise in fashion terms), for example. Such oddities could only be produced by mixing other colours – but how this was to be done caused confusion. Over time, Newton's successors started using a wheel or 'top' with different colours on, which was spun so that the colours seemed to combine in the eye. Professor Forbes at Edinburgh had repeatedly attempted to produce white through a combination of variants of red, yellow and blue on a wheel – but had failed. Similarly, Forbes had used one of the artist's most familiar combinations – mixing yellow and blue to make green – and discovered that, bizarrely, his spinning wheel appeared to produce not green at all, but a dirty shade of pink.

The true primaries

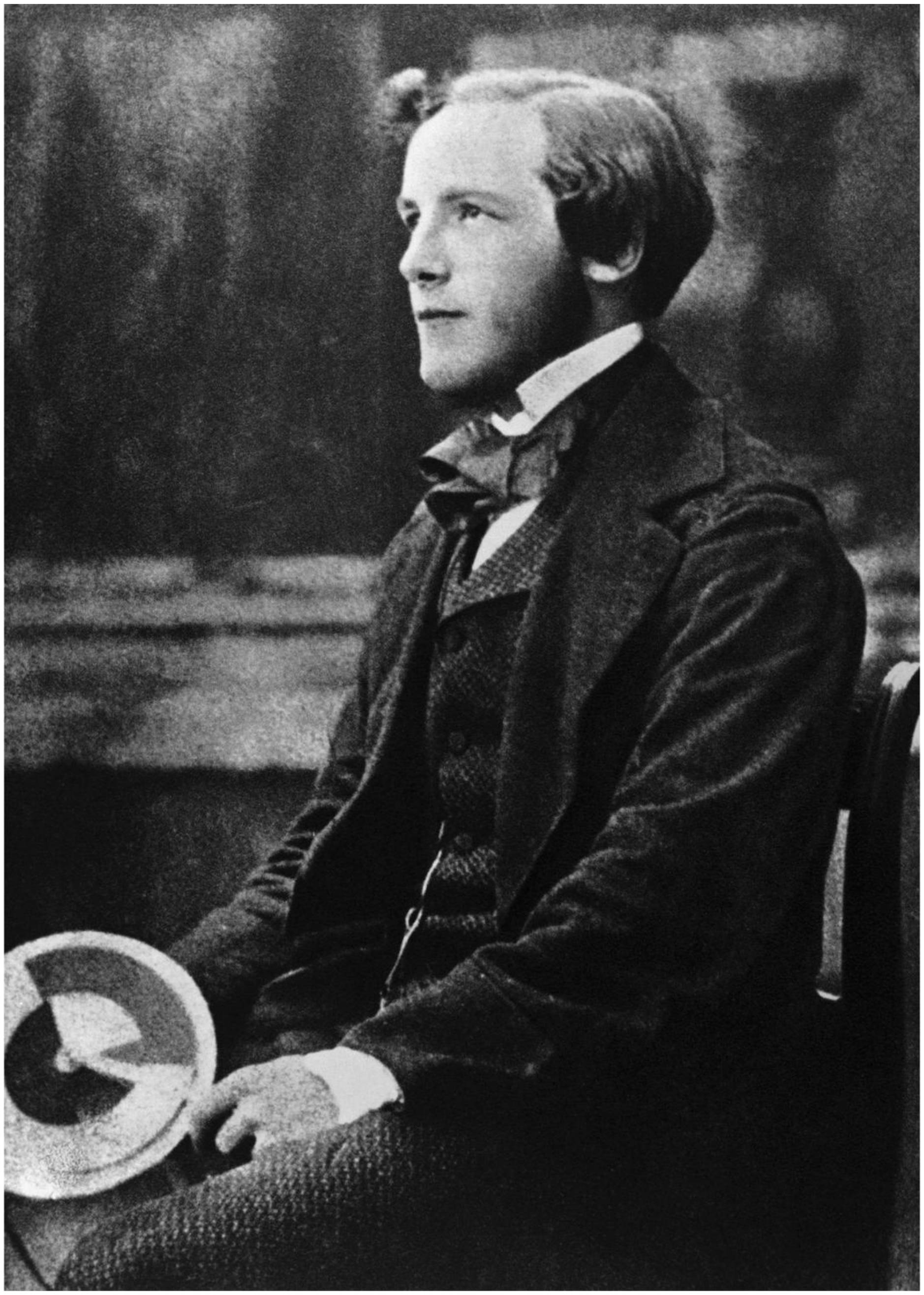
It was Maxwell, now what we'd call a graduate student, who followed up the idea of German physicist Hermann von Helmholtz, building on Newton's observations, that there were two different processes involved: that colours in light added together to produce new shades, while colours in a pigment were subtractive (i.e. they took away some of the colours of light) and had to be treated separately. As Newton had suspected, when we see an object as a certain colour – a red postbox, for example – what our eyes actually detect is the light that is re-emitted by the box. If white light, with all the colours in it, is falling on the box and we see red, then the pigments in the paint have absorbed the other colours. And when we mix pigments, such as yellow and blue, the resultant colour we see (green in this case) is what's left when the rest of the colours in the light have been absorbed by those two pigments.

This meant that the artist's primary colours weren't really primaries at all, but were the leftovers when the primaries were absorbed, the diametric opposites of primaries,[††] which modern scientists would probably have called anti-primaries. Through a combination of experiment and logic, Maxwell realised that the true primaries of light (as opposed to pigments) were in reality red, green and blue or violet – when he made up a colour disc with these colours and spun it, he saw white. In making this change he was going against his old Edinburgh professor Forbes who stuck (with many of his contemporaries) to the earlier idea of red, yellow and blue as the primary colours of light, despite the failure of their experiments.

This wasn't enough for Maxwell, though. He built his own totally new version of the colour top, using three paper discs, one for each primary colour, so he could spin different combinations of red, green and blue to study the resultant perceived colours. These discs were provided by the Edinburgh printer and artist David Hay, who had inspired Maxwell's teenage paper on drawing curves, and whose colour printing was considered to be among the best in Great Britain. The term 'top' suggests a self-supporting spinning device, but in reality, his mechanism consisted of a flat metal disc to support the paper sheets, pivoted on a handle, so it was shaped something like a round skillet with a spinning pan.

In an early manuscript on the subject from February 1855, Maxwell described the device as a 'teetotum' (an alternative word for a top). He tells us:

> It may be spun by means of the fingers but if more speed is required it ought to be spun by means of a thread wound round the part of the axis immediately below the disc. This is best done by slipping the knot on the thread behind the little brass pin under the disc and after winding it up placing the axis vertical & so that the two grooves in it rest in the two hooks belonging to the brass handle. When the string is pulled, the hooks keep the axis vertical and thus the teetotum may be spun steadily on the smallest table or tea tray.



Maxwell aged 24 with one of his colour wheels in 1855.
Getty Images

It is entirely possible that the idea of constructing his colour top had its inspiration in an entertainment from Maxwell's youth. One of his favourite toys as a child was the phenakistoscope, more mundanely known as the magic disc. This spun a disc with a series of illustrations drawn around its edge. The disc was viewed from the rear through a series of slots in the disc, reflecting the images in a mirror to produce the effect of a very short moving picture. Maxwell drew the pictures for many of his own mini-movies to spin on the magic disc, with subjects covering everything from the cow jumping over the Moon to a dog catching a rat. The merger of the still images in the brain to produce a combined effect could well have suggested a similar approach in the top.

Maxwell's colour top also had room for a fourth colour which was in a continuous circle around the centre of the disc. This meant that he could adjust the amounts of each primary to match the colour represented in that circle. He went on to produce a mathematical formula relating the percentages of the primaries to the resultant hue.

From his formula, Maxwell was able to produce a 'colour triangle' which started with the three primaries in the corners of an equilateral triangle and mixed the amounts of the colours according to the distance to the corners (see Figure 1). An important outcome of this work was the realisation that what we perceive as the colour in a beam of light is not the same thing as the absolute colour of the light used. While monochromatic light of a particular wavelength will be seen as, say, orange, the brain also combines the input from the different colour-determining sensors in the eye, known as cones, to enable the colour to be produced from a mix of the primary colours.

Similarly, Maxwell was able to use his triangle to understand the detail of how pigments appear to have particular colours. For example, if you shine white light onto a pigment that strongly absorbs the middle of the spectrum, around green, the result will be that red and blue wavelengths are mostly re-emitted, producing magenta – which is effectively anti-green. And the old artist's favourite of mixing yellow and blue to produce green works because cyan pigment mostly absorbs red, while yellow pigment mostly absorbs blues, leaving only green to be re-emitted.

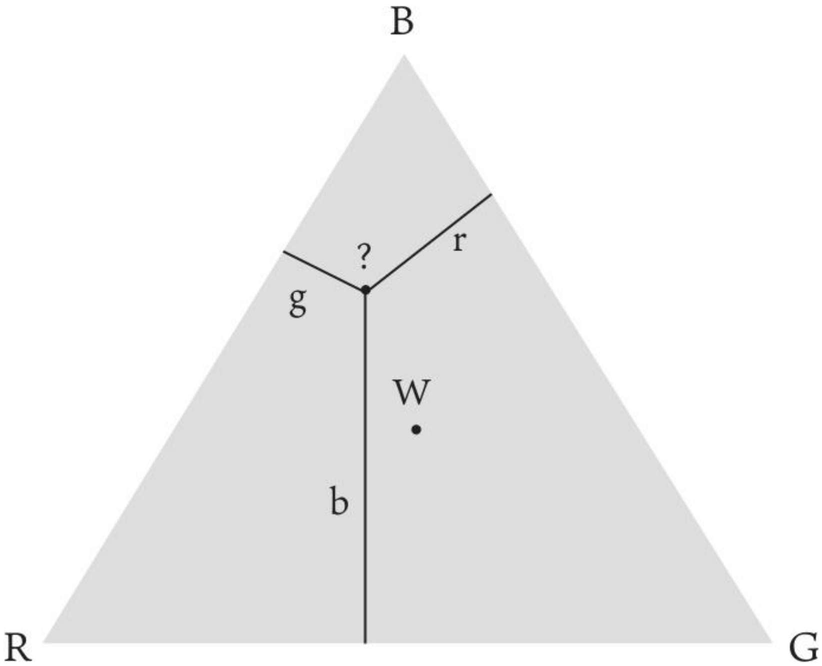


FIG. 1. *Each corner of the colour triangle corresponds to a single primary colour. The colour at the point marked '?' mixes r of red, b of blue and g of green – the central W point has equal amounts of each colour, producing white.*

A peculiar inability

Maxwell notes that some individuals have a 'peculiar inability' to distinguish certain colours – his work on the perception of colour went hand in hand with a deep interest in those who were colour blind, suffering from 'Daltonism' as it was often known then, after the Manchester chemist John Dalton, who suffered from the condition and was one of the first to study the phenomenon scientifically. Maxwell also records that the most interesting result is that 'different eyes in similar circumstances agree to the most minute accuracy [on a colour] while the same eyes in different lights give different results'.

So, he had discovered, our perception of colour is strongly affected by lighting etc. but is remarkably consistent between individuals who have normal colour vision. But Maxwell, with a good scientist's caution, was not willing to expand his observations too far from the small sample he originally had access to. He noted: 'These results however can be completely verified only by a large number of observations.' For the rest of his working life, he would invite visitors to try out a range of colour mixing devices he invented to widen his sample, and would ask friends both to take the test and to bring forward anyone they knew who didn't see colour the same way as the majority.

Maxwell followed up his initial manuscript with a paper presented to the Royal Society of Edinburgh, where he brought out further his idea that colour blindness was typically caused by one of the three colour systems in the eye being defective. If so, he felt it should be possible to make combinations of colour on the colour top which identified what sensitivities were missing in people's colour perception.

He also spent some time trying to match a range of colours using different combinations on his top. By now Maxwell had settled firmly on red, green and blue as the definitive primary colours of light. Producing a good range of browns seems to have given him the most problems. In a letter to William Thomson, who had expressed doubts about achieving this colour at all by mixing light primaries, Maxwell noted: 'I have been thinking about what you say about Brown. I have matched ground coffee tolerably though the surface is bad chocolate cakes & improvised browns with black, red & a little blue & green.'

Maxwell would never know the practical importance of his work, but his colour triangle gave an essential understanding that allowed us eventually to produce the colour screens we now use on everything from TVs to computers and phones. Each coloured pixel on the screen is made up of separate red, green and blue elements, and their relative proportions are used to produce the whole range of millions of colours typically on display … all based on Maxwell's ground-breaking approach. As was the case in many such developments, there was parallel work going on – as we have seen, German physicist Hermann von Helmholtz came to similar conclusions on the way that colours in light added, but pigments subtracted.

Once Maxwell had clearly demonstrated the colour model we now use, it might be expected that others would quickly fall into place and accept it. But the red, yellow, blue model was so strong, and so firmly supported by the artistic fraternity, that it took years of repetition and demonstration for Maxwell to get broad agreement. As late as 1870, a good fifteen years later, he wrote to a former Trinity College friend, Cecil Monro:

> Mr W. Benson, architect, 147 Albany Street, Regents Park, N. W., told me that you had been writing to Nature, and that yours [supporting Maxwell] was the only rational statement in a multitudinous correspondence on colours … No other architect in the Architect's Society believes him. This is interesting to me, as showing the chromatic condition of architects.

Quantifying Faraday's fields

Light and colour vision were not, however, Maxwell's only, or even his primary interest. Ever since his childhood experiments at Glenlair he had been intrigued by the magical-seeming ability of magnets to influence other pieces of metal from afar, and at university he had become an ever more enthusiastic devotee of Michael Faraday, following with interest Faraday's many experiments with electricity and magnetism. Faraday's idea of magnetic and electrical fields with their lines of force would fascinate Maxwell.

The field approach was generally regarded as an interesting model for electricity and magnetism – a useful way to think about them – but not one that would ever be susceptible to mathematical study. (Faraday was mocked by some of his contemporaries for his lack of mathematical expertise.) To work mathematically with electromagnetism, a similar approach to that applied to gravity was used. This involved an 'inverse square law' – forces acting remotely which decreased with the square of the distance away from point sources.

Maxwell was sure that Faraday's ideas were sound and looked for a way to provide a mathematical basis for those mystical-sounding lines of force that were central to Faraday's understanding. As we have seen, Maxwell seems to have been driven by his relatively unusual academic background. Cambridge was very strong on mathematics, but tended to apply it to the sciences with which maths had always been strongly linked, such as astronomy. Edinburgh, by contrast, gave Maxwell the grounding in electromagnetism, but would not have encouraged taking a mathematical approach to it. Maxwell was able to bring the two approaches together.

The idea of a field is something like a three-dimensional version of a contour map. Any point on the map has a particular value for the height of the land at that location, and the contours on the map are the equivalents of lines of force, joining points of equal height. The equivalent in electromagnetism would be joining points with equal strengths of electrical or magnetic fields. But the complexity of moving to a field model was greater than the need to move from a two-dimensional map to a three-dimensional field. The values at each point on a map are just numbers reflecting the altitude – mathematicians refer to such number-only values as scalars. But each point in an electrical or magnetic field represents both a size and a direction – they are called vectors.

In the 1850s, the mathematics needed to handle vectors was yet to be fully developed, but Maxwell was aware of the basics and of some of the requirements to analyse a field mathematically. He asked for help from fellow Scot William Thomson, who had already done some work on electricity using vectors, basing it on his better-developed study of the flow of heat. Thomson had discovered that, by some strange natural coincidence, the equations describing the strength and direction of the 'electrostatic' force between electrical charges were the same as those that dealt with the rate of flow and direction of flow of heat.

Maxwell took Thomson's guidance on the mathematics of vectors, but went his own way on applying it. He thought of electricity as behaving like a fluid that was flowing through a porous substance, while magnetism seemed like vortices within the fluid. The lines of flow of his fluid corresponded to Faraday's lines of force, and the speed of the flow provided the 'flux density' which was a measure of the strength of the electrical or magnetic field. The difference in porousness of the materials that the imaginary fluid flowed through corresponded to the way that different substances reacted to electrical and magnetic fields.

It ought to be stressed, however, that Maxwell did not think that electricity actually was such a penetrating fluid. There was a clear lesson from the study of heat to be learned here. For about 100 years, most of the work on heat assumed that there was a real, invisible fluid called caloric, which flowed from a hot object to a colder one that it was in contact with. The caloric theory had had some success in explaining how heat behaved, but ultimately it proved ineffective, and a better explanation that considered heat to be the kinetic energy of atoms and molecules in a substance took over.

Maxwell's fluid was never intended to be the electromagnetic equivalent of caloric. His fluid was purely imaginary and the flow of his fluid was *not* electricity itself, but rather was an *analogy* for the strength of the electrical and magnetic fields. And it worked surprisingly well. One of the results that Maxwell got pretty much for free out of this model was that by using a non-compressible fluid to represent the field, it meant that there was always the same amount of fluid in the same volume, which produced an interesting mathematical result.

If there was always the same amount of fluid in the same volume, the flow of fluid would drop off with the square of the distance from the source. If the same amount of fluid travelled through a wider and wider space, then its rate of flow depended on the surface area of a cross-section of that space. Think, for instance, of a liquid moving out through a funnel in the reverse direction from usual, going from the narrow end to the wider one. If the fluid can't compress or stretch and has to fill all the space available, then it will have to be going a lot slower at the wide end of the funnel than at the entrance. The speed it moves at will depend on the size of the opening.

Similarly, if we think of liquid emerging from a point and heading out in all directions, then the surface area of the 'opening' is just the surface area of a sphere – $4 \pi r^2$, where r is the radius of the sphere – so the surface area the fluid has to fill increases with the square of the distance from the centre. We see the fluid moving slower – which in Maxwell's analogy means the strength of the field dropping off – reducing in speed with the inverse square of the distance from the source. This was exactly what happened in experiments on the electromagnetic field.

As noted above, Maxwell always saw his approach as an analogy – a model of reality that did not have any direct resemblance to what was actually happening, but which produced useful results. He commented in his paper describing his ideas, named *On Faraday's Lines of Force*:

> I do not think that [the fluid analogy] 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.

Not only did Maxwell's fluid model fit with Faraday's force fields while predicting the inverse square law of the traditional 'action at a distance' mathematics, it was better than the action at a distance approach when dealing with the boundaries between materials. Though Maxwell could not see how to take the step into modelling changing electrical and magnetic fields that would be necessary to deal with many of the phenomena that had enabled Faraday to come up with the electrical generator and motor, this was impressive stuff for someone who had only just graduated and was in his early twenties. As well as presenting his ideas to the Cambridge Philosophical Society, Maxwell also sent his paper *On Faraday's Lines of Force* to his hero, Michael Faraday, in London.

Faraday was by now in his sixties, but was still working at the Royal Institution and replied to Maxwell:

> I received your paper, and thank you very much for it. I do not venture to thank you for what you have said about 'Lines of Force', because I know you have done it for the interests of philosophical truth; but you must suppose it is work grateful to me, and gives me much encouragement to think on. I was at first almost frightened when I saw such mathematical force made to bear upon the subject, and then wondered to see that the subject stood it so well.

For the benefit of working men

Faraday, as we have seen, had not had the benefit of a university education. The closest he came to formal training before beginning work at the Royal Institution was to attend the City Philosophical Society, a group set up with the specific intention of helping those from humble backgrounds to better themselves. Although Maxwell had a more privileged upbringing, he was aware from his contacts back at Glenlair of the limited opportunity for working men to improve their education, and also how Faraday had benefited from the 'Phil Soc'. And, being Maxwell, he could not stand back and assume someone else would sort the problem out.

At Cambridge, Maxwell was one of the founders of the Working Men's[‡‡] College, which provided evening classes for self-improvement. Not only did he give some of the lectures himself, he toured local businesses, asking them to allow their men to leave their jobs early on lecture nights. In a letter to his father, written in March 1856, he noted:

> We are also agitating in favour of early closing of shops. We have got the whole of the ironmongers, and all the shoemakers but one. The booksellers have done it some time. The Pitt Press keeps late hours, and is to be petitioned to shut up.

This enthusiasm for outreach and the betterment of those from humble beginnings would continue through future posts where Maxwell would regularly get involved with local working men's educational organisations, such as the mechanics' institutes often found in industrial towns and cities.

Maxwell soon became comfortable in his new position as a graduate student, though he still cherished his summers in Scotland, whether at Glenlair or spending time with relatives. In 1854, this resulted in his first recorded encounter with love. Maxwell spent a week with the Cays, his mother's family, in the Lake District. Among his mother's brother's children on the trip was Maxwell's cousin Lizzie – fourteen to his 23. There seems little doubt that Maxwell fell in love. Lizzie's age was less of a concern then than it would be now at a time when girls often married at sixteen after a lengthy courtship. However, the family seems to have been set against the match.

There was awareness of the risks of marrying such a close relation as a first cousin, even though it was relatively common among the upper classes, notably in the royal family where it occurred frequently. The Clerks and the Maxwells had over the century or so since their first intermarriage frequently wed cousins. But, for whatever reason, it was not to be. If Maxwell and Lizzie exchanged any letters they have not survived – the story of their brief passion has only been related via Lizzie's daughter, who at the time was aged 90.

Another personal event of that year was Maxwell becoming a Justice of the Peace – a magistrate. It's not clear how frequently (if at all) Maxwell carried out the role, which was often nominally taken by the lord of the manor, but it shows an awareness of his personal responsibilities as a member of the establishment that would come through strongly when he later inherited the Glenlair estate.

One interesting 'might have been' turned up at the start of 1855. His friend Cecil Monro wrote to Maxwell saying, 'NEWTON MUST BE TRANSLATED, and you are the one to do it'. This was a reference to Isaac Newton's masterpiece, the lengthy (and sometimes near-impenetrable) work *Philosophiae Naturalis Principia Mathematica,* usually just known as the *Principia.* This three-volume book contains both Newton's laws of motion and his work on gravitation, and was originally published in Latin. It had been translated into English in 1729 by Andrew Motte, but by the 1850s that version was seeming too archaic to be used as a serious scientific document.

It wasn't entirely surprising that there was demand for an English version of the most important work by the man generally regarded at the time as the greatest English scientist, if not the world's. Monro drolly pointed out that Maxwell's Latin was good enough 'for practical purposes … [though] it is very true that you don't seem ever to have displayed such acquaintance in your college examinations'. Monro may have known that a significant reason why Maxwell was yet to be elected a Fellow of Trinity College was because it was considered that he needed to attend more to the classics.

Maxwell replied at his most whimsical:

> Dear Monro
> It is a fearful thing to answer when a man tackles you with arguments. I wont argufy at all, leastways not with them as tries to argufix me. I w^{d} be most happy to give any assistance in my power to the translator of Newton, short of taking on the work of his hands. For that I am not prepared. I am prepared to refuse resist & rebel. I w^{d} as soon think of translating Butlers Analogy[§§] for the Mathematical Journal.

It was not to be.

This letter and a number of others from Maxwell were written from 18 India Street in Edinburgh, two doors down from the Clerk Maxwells' old house. Their own place, 14 India Street, had been rented out once Glenlair was completed, and the Maxwells never lived there again, but when Maxwell had gone to Cambridge, his Aunt Isabella moved from her house in Heriot Row to India Street, and it was number 18 that Maxwell used as a pied-à-terre in Edinburgh.

A new destination

It's quite possible that Maxwell, getting well established in Cambridge, would have taken his ideas on electricity and magnetism further at this stage of his career. But in February 1856, his old professor James Forbes wrote to him about an opening at Marischal College in Aberdeen. The university was looking for a Professor of Natural Philosophy, which Forbes thought was a position that would ideally suit Maxwell.

As Forbes put it:

> I have no idea whether the situation would be any object to you; but I thought I would mention it, as I think it would be a pity were it not filled by a Scotchman, and you are the person who occurs to me as best fitted for it.

There is no evidence that Maxwell had ever been to Aberdeen before, a good 120 miles from Edinburgh and altogether less sophisticated than the capital. And there was no doubt that the country boy had had many of his rough edges rubbed off at Edinburgh and Cambridge, perhaps giving him some expectation of lively intellectual surroundings. But gaining a professorship would be an impressive position to kickstart his career.

Forbes was also at pains to point out that he had no influence over this appointment, as it was in the hands of the Crown, though it's not clear if this suggests that otherwise he would have attempted to bias things in Maxwell's favour. Maxwell noted in a letter to his father a couple of days after receiving the notification from Forbes:

> I think the sooner I get into regular work the better, and that the best way of getting into such work is to profess one's readiness by applying for it. The appointment lies with the Crown – that is, the Lord Advocate[¶¶] and the Home Secretary. I suppose the correct thing to do is to send certificates of merit, signed by swells, to one or other of these officers.

The idea that Maxwell should become a professor at the age of 24, having only graduated with a BA less than two years earlier, would seem outrageous now. However, modern academic positions have a much stronger hierarchy and career progression than was the case at the time. In practice, Maxwell had everything that was needed for the post, since he had been made a Fellow of Trinity in October 1855, which gave him his academic CV. His friends William Thomson and Peter Tait had both been awarded professorships at younger ages – Thomson became Glasgow's Professor of Natural Philosophy at the tender age of 22, while Tait became the Professor of Mathematics in Belfast at 23.[||||]

With his application sent off, and a flurry of requests for support sent to the great and the good, which this kind of royal appointment required, Maxwell returned to Glenlair for the Easter vacation. His father had been suffering for some time from a lung infection, which got progressively worse over the following days. John Clerk Maxwell died on 3 April, leaving Maxwell with a major new responsibility as head of the Glenlair estate.

Three weeks after his father's death, Maxwell wrote to his friend Lewis Campbell:

> When the term is over I must go home and pay diligent attention to everything there, so that I may learn what to do. The first thing I must do is carry on my father's work of personally

> superintending everything at home, and for doing this I have his regular accounts of what used to be done, and the memories of all the people, who tell me everything they know.

It was not taken for granted, then, that Maxwell would continue his academic work, but in the same letter he made it clear that his father had felt that Maxwell could achieve the appropriate balance.

> As for my own pursuits, it was my father's wish, and it is mine, that I should go on with them. We used to settle that what I ought to be engaged in was some occupation of teaching, admitting of long vacations for being at home; and when my father heard of the Aberdeen proposition he very much approved. I have not heard anything very lately, but I believe my name is not yet out of the question in the L^{d} Advocate's book.

Maxwell was correct – his name was at the top of the list and he was duly awarded the position. He would spend the remainder of the term at Cambridge and the long summer vacation putting things in order at Glenlair. He found time in that vacation to undertake some work on colour and on Saturn's rings (more on this later), but there is no doubt that the responsibilities he had inherited from his father came first.

In a letter to a university friend, Richard Litchfield, he noted:

> I have certainly no time now & I have much more occupation than I expected such as to examine into the state of two sets of houses & provide wood &c for roofing them and workmen to do it and various things of this kind also to enquire into the merits of the younger clergy and the sentiments of the parish on the subject, for our minister died unexpectedly this week and there are no resident proprietors in the parish except the patron of the living who is a lady of Romish persuasion [i.e. Catholic] who has been for a year in Edinburgh and denies herself to all her friends.

Despite the unexpected workload, Maxwell was able to bring Glenlair under his control and made the move to Aberdeen in the autumn.

Notes

1 – John Clerk Maxwell's list of suggested places for his son to visit in Birmingham is noted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 3.

2 – Maxwell's observations on Cambridge colleges before applying, noted by Mrs Morrison, are recorded in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 132.

3 – Maxwell's experiment with working during the night was in a letter to Lewis Campbell dated 11 March 1851, written from his lodgings in King's Parade, Cambridge, quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 155.

4 – Lewis Campbell's note that Maxwell ironically engaged with electro-biology and table-turning is from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 166.

5 – John Clerk Maxwell's letter to his son on the dangers of electro-biology is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 156.

6 – Maxwell's concern on the way Faraday was treated after explaining the phenomenon of table-turning is from a letter to the Reverend C.B. Tayler, written from Trinity College, Cambridge on 8 July 1853, quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 189.

7 – Lewis Campbell's description of Maxwell's appearance while at Cambridge is from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 162.

8 – Maxwell's letter to his wife from Trinity College, Cambridge, written on 4 January 1870, is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 499.

9 – Maxwell's poem 'A Vision' is reproduced in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 632.

10 – Maxwell's letter to his aunt, Miss Cay, on using his instrument to see into eyes, particularly of dogs, from Trinity College, dated Whitsun Eve, 1854, is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 208.

11– Maxwell's manuscript on the colour top is 'Description of the Chromatic Teetotum as Constructed by Mr J.M. Bryson, Optician Edinburgh', from 27 February 1855, reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990) pp. 284–6.

12 – Maxwell's paper 'Experiments on Colour as Perceived by the Eye, with Remarks on Colour-Blindness', based on his initial colour top work, was published in *Trans. Roy. Soc. Edinb.,* 21 (1855): 275–98 and its abstract is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990) pp. 287–9.

13 – Maxwell's letter to William Thomson which mentions the difficulties of reproducing brown colours was written from Trinity College on 15 May 1855 and is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990) pp. 305–13.

14 – Maxwell's letter to Monro on colour theory, written from Glenlair on 6 July 1870, is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 346.

15 – Maxwell's description of his fluid model of electromagnetism as not containing the shadow of a theory is from Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 207.

16 – Maxwell's letter to his father about getting shops to shut early for the Working Men's College was written from Trinity College, Cambridge on 12 March 1856 and is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 404.

17 – Cecil Monro's letter on translating Newton, dated 20 January 1855, and Maxwell's reply from 18 India Street, Edinburgh, dated 7 February 1855, are reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 280.

18 – Professor Forbes' letter to Maxwell recommending he consider the position at Marischal College is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 250.

19 – Maxwell's letter to his father about applying for the position at Marischal, written at Trinity College, Cambridge on 15 February 1856, is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 251.

20 – Maxwell's letter to Lewis Campbell about his responsibilities after his father's death was written from Trinity College, Cambridge on 22 April 1856 and is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 405.

21 – Maxwell's letter to Richard Litchfield about his unexpected workload at Glenlair was written from Glenlair on 4 July 1856 and is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 410.

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[*] John Clerk Maxwell was a great enthusiast for the importance of visiting places as a means of self-improvement. When Maxwell was getting near to his final exams at Cambridge and suggested a few days' break over the vacation to visit a friend in Birmingham, John wrote to him with a list of suggested venues his son could take in. These included 'armourers, gunmaking and gunproving—swordmaking and proving—*Papier-mâchée* and japanning—silver-plating by cementation and rolling—ditto, electrotype—Elkington's works—Brazier's works, by founding and by striking out in dies—turning—spinning teapot bodies in white metal, etc.—making buttons of sorts, steel pens, needles, pins, and any sorts of small articles which are curiously done by subdivision of labour and by ingenious tools—glass of sorts is among the works of the place, and all kinds of foundry works—engine-making—tools and instruments—optical and [philosophical], both coarse and fine.' Ever the attentive son, Maxwell began with the glassworks.

[†] It was, and to some extent still is the fashion to refer to going 'up' to Cambridge from any point of the compass, but from Maxwell's youthful viewpoint where all of England was in the south, it surely was 'down'.

[‡] Hidden.

[§] Cambridge rooms had (and older ones still do have) an odd contrivance of inner and outer doors with only an inch or so between them. The inner door was the 'oak' and the outer door the 'sporting door', closed to indicate that the occupant did not want to be disturbed – having a shut sporting door was referred to as 'sporting the oak'.

[¶] 'Tripos', pronounced 'tri-poss' rather than 'tri-pose', is the unique Cambridge system describing the exams necessary to gain a degree in a particular discipline. The word is said to come from the name of the three-legged stool that was used during oral examination, though there is limited evidence for this. Despite the 's' on the end, it's singular.

[||] Another Second Wrangler was Maxwell's somewhat older friend, the University of Glasgow physics professor William Thomson. Thomson had apparently been so obviously the favourite for Senior Wrangler that he didn't bother to check the result, instead sending a college servant along to the Senate House where the results were posted to see whom he should commiserate with for being Second Wrangler. The servant returned to say, 'You, sir.'

[**] University members were forbidden from attending the fair and would have been at risk of being arrested by the university's proctors, so the fair was cunningly sited just outside the limits of their authority, on Stourbridge Common.

[††] Even here, the artists got it wrong with their 'primaries'. The primary pigments are cyan, yellow and magenta (take a look at the inks in your colour printer) – the blue, yellow and red colours that we still teach at school are just approximations to these. But, as we demons know all too well, you can't expect reliability from artists.

[‡‡] It would be wrong to criticise in retrospect the fact that the Working Men's College was aimed at men only. Maxwell was a man of his time and gave limited consideration at this point in his career to women's education.

[§§] This was Joseph Butler's book *The Analogy of Religion, Natural and Revealed, to the Constitution and Course of Nature* – which was anything but a mathematical title.

[¶¶] The Lord Advocate was the senior legal and political role in Scotland, a position at the time held by a James Moncrieff.

[||||] Nor was he as precocious as the Swiss mathematician Leonhard Euler, who became a professor at St Petersburg aged nineteen.

Demonic Interlude III

In which atoms become real and heat gets moving

It's arguable that the summer of 1856 was when JCM made the transition from a youth to a man. His career had made the leap from graduate student to professor, he lost his father – with whom he had been very close – became the laird of Glenlair, and had moved from a city where his intellect was a comfortable fit to a more remote location where he would stand out more than most.

As Aberdeen is going to be the location where our young professor starts to take on the matters that will bring me into being, it's important we get a little background on the matter of atoms (and molecules), and of heat.

Atoms exist

At the heart of JCM's thinking on thermodynamics and the mechanics of gases was the idea that atoms and molecules were real. This is such a trivial point today that it's worth emphasising that in the 1850s the majority of scientists were at best ambivalent as to the existence of atoms. They were considered a useful concept for explaining the way elements combined in chemistry, but were thought probably not to be actual physical things. Yet it was their reality that spurred on the thinking that would be JCM's biggest claim to fame in his own era.

Back in the fifth century BC, the Ancient Greek philosopher Democritus dreamed up the concept of atoms.[*] It seems quite a reasonable idea. If you cut stuff up, you get smaller and smaller pieces of that stuff. Eventually, Democritus argued, you'd get a piece that was so small that it was impossible to cut it any further. This was not because your knife wasn't sharp enough, but because there was nothing more to divide. He called such a piece uncuttable: *atomos.*

While there was a degree of logic to the thinking, the trouble was that as a scientific theory it didn't have a lot of value because it didn't explain anything. Democritus did not combine his concept of atoms with any idea of elements, which would have made it possible to simplify the description of matter. But a competitor, Empedocles, did come up with a theory of four elements: earth, air, fire and water. Though wrong, this had more practicality than the early atomic theory and was built on by one of the great philosophers: Aristotle.

Active in the fourth century BC, Aristotle brought in a fifth element, the quintessence, which was the substance from which everything from the Moon outwards was supposed to be made. In principle, there was nothing to stop Aristotle from combining his elements with the atomic theory. Unfortunately, though, he had an aversion for totally empty space. He did not like the concept of a vacuum or void.

The logic behind this aversion was sometimes convoluted, but the simplest argument Aristotle made, ironically to modern eyes, was that if there were a void, then something like Newton's first law of motion would apply – there was no reason why anything moving should stop unless something forced it to do so. As this didn't seem to happen in the nature he observed, Aristotle thought that the concept was flawed and so a void could not exist.

Without a void or vacuum there couldn't really be atoms, as the atoms would have to fit together in such a way that they totally filled empty space – something that was only possible with a very small number of shapes, such as a cube. Assuming that at the very least you needed four or five different types of atom, it simply seemed impossible to have atoms without space in between them. And Aristotle (with the stubbornness that is typical of some of you humans) wouldn't allow it.

Aristotle's views were largely accepted unchallenged through to Galileo's time, and it took a considerable period longer before atoms would be taken seriously. It was only really in the 1800s that atoms began to take hold as a realistic scientific concept. This was largely due to the work of John Dalton, an English Quaker who spent much of his working life in Manchester. Dalton was largely self-educated, unable to attend university because of his religious beliefs, as attendance at the time required membership of the Anglican Church.

Apparently as a result of experiments on gases, right at the start of the nineteenth century, Dalton devised the concept of atom-based elements, where each of the spherical atoms of any particular element had the same weight. As early as 1803 he was beginning to note down the relative weights of these atoms, starting with the lightest, hydrogen. He also considered that many substances were compounds, made up not of individual atoms, but molecules which combined two or more atoms.

There were limits to Dalton's work. His equipment was mostly self-made and of poor quality even by the standards of the day. He got some of the relative weights wrong and made the mistake of assuming that compounds would be made up of the simplest possible combinations – so he thought, for example, that water was HO with a single hydrogen atom, rather than the pair of hydrogens present in the familiar H_2O.

He also had a mental model of atoms as spheres of different sizes, which seems to have prevented him from noticing the now-obvious implication that if 'bigger' atoms had multiples of the weight of hydrogen, perhaps they were made up of multiple hydrogen atoms (or the same subatomic particles as we now know). It didn't help that, though Dalton often wrote the relative weights of his elements as round numbers, he did not think these were exact values, but rather considered them to be convenient approximations.

Again, with 20:20 hindsight it may seem that the concept of atom-based elements was so obvious that atoms should have been widely accepted by the time JCM started thinking about them. However, the general feeling was that they provided a useful model, but did not necessarily reflect any actual structure within a substance, just as JCM didn't think that electricity was a fluid but found it a useful analogy. Matter's behaviour could be well described as if it were a collection of atoms, but that didn't mean they were real things you could pick up with tweezers and look at.

It wouldn't be until after 1905 – when Albert Einstein, in one of his first great papers, showed that calculations of the size of molecules could be made – that the reality of atoms was increasingly considered mainstream. It's notable that when JCM's friend Peter Tait was writing a textbook with William Thomson, Tait ruefully commented to a friend: 'Thomson is dead against the existence of atoms; I though not a violent partisan yet find them useful in explanation.' Yet a handful of scientists in the mid-nineteenth century made the assumption that atoms and molecules were indeed real – JCM among them.

A better model of heat

The reason for JCM's interest in the atomic was not so much to consider the nature of matter directly, but rather to deal with a pressing problem of the day – how to explain the workings of heat. For thousands of years, the only real interest in heat was whether or not it was warm enough to be comfortable or a fire was hot enough to cook food.[‡] But the nineteenth century saw the steam engine become the dominant power source for industry and travel. Steam was king – but understanding the true workings of the steam engine required the development of a new branch of physics – thermodynamics – and JCM would be at the heart of this work.

We've already met the second law of thermodynamics when I introduced myself, but let's take a step back to discover where the whole business came from. As we have seen, the prevalent theory on the nature of heat at the start of the nineteenth century was caloric theory. This considered heat to be a fluid called caloric. One of the essential properties of caloric was that it repelled itself. This meant that if you had a hot object and a cold one in contact, there would be more caloric in the hot than the cold. This meant more repulsion in the hot thing's caloric, so the caloric from there would naturally move into the cold object until a balance was achieved. The hot object would get cooler and the cold object hotter. (It's that second law again.)

This theory had proved surprisingly effective, bearing in mind it was wrong. As well as supporting the second law, it predicted that a gas should try to expand as it got hotter, as there was more caloric to fit into it. In 1824 the French scientist and engineer Sadi Carnot developed the first concepts in thermodynamics, explaining the limits on the efficiency of steam engines, entirely based on caloric theory. The man who took Carnot's ideas and brought them into a more modern viewpoint of thermodynamics was JCM's frequent correspondent and friend, William Thomson, later Lord Kelvin.

Thomson's work in formulating thermodynamics was aided by input from an unlikely source – the brewer James Joule (who, in a neat symmetry, had been tutored by Dalton). It was Joule who helped kill off caloric theory by showing that heat was not a special fluid in its own right, but simply a manifestation of energy, which could be reliably and consistently converted to and from mechanical energy. We also need to throw in the contribution of the German physicist Rudolf Clausius who worked in parallel with Thomson (and Maxwell) on thermodynamics.

The outcome of these collective geniuses at work was to develop several laws of thermodynamics. The two biggies were the first law – the conservation of energy – stating that energy can neither be made nor destroyed, but is just transferred from one form to another (these forms, most importantly, including heat); and my demonic law, the second law. This started in the days of caloric – the idea of the fluid naturally moving from hot to cold – but would become formalised in terms of both heat flow and entropy.

Bearing in mind the identification of heat as energy, it became important to understand how that energy manifested in matter. One common and well-understood form of energy was kinetic energy, the energy of movement. And, in gases at least, if matter could be considered to be made up of actual atoms and molecules, then the movement of those tiny particles could well provide the energy that was described as heat. The faster the particles moved, the hotter the gas.[‡] It was for this reason that JCM would take atoms on board.

However, we're getting ahead of ourselves. The youthful James Clerk Maxwell is about to take up his post as Professor of Natural Philosophy at Marischal College. We're off to the granite city.

Notes

1 – Tait's observation that Thomson was 'dead against atoms' was in a letter to Thomas Andrews written on 18 December 1861, noted in Crosbie Smith and Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge University Press, 1989), p. 354.

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[*] His teacher, Leucippus, may also have been involved, but there is little evidence of his existence and it's possible Democritus simply invented Leucippus as a kind of 'fake news' support for his theory – if so, he was my kind of guy.

[†] Or for us demons to torment souls in hell.

[‡] In reality it's a little more complex than this, as energy can also be tucked away in the vibrations of molecules that aren't moving freely and in the energy levels of electrons around atoms, but this is a good starting point.

Chapter 3

The young professor

Marischal College is not a name that you will find on the British university scene any longer, but when the fresh-faced 24-year-old Maxwell was appointed Regent and Professor of Natural Philosophy in April 1856, starting work in August, it was a well-known constituent of the Scottish academic establishment. Though the vast, dour grey granite main building still stands on Broad Street at the heart of Aberdeen, it is now used by the city council. However, in Maxwell's day, the college was a respected institution with a solid history stretching back to 1593. Like all ancient colleges at the time, the education it provided was broader than a modern university curriculum, though most students would have been on a path towards a career in law, the church, medicine or education.

A city divided

When Maxwell arrived at his new workplace, there was already talk in the air about the college's demise. Scotland had, at the time, five universities, and two of them were in the small city of Aberdeen, then with a population of only around 35,000 people.* Marischal shared the city with the hundred-years older King's College – this was a pre-Reformation foundation and its Catholic roots were not considered ideal for educating ministers of the Protestant kirk. In reality, 'shared the city' was not strictly true: the city itself was split in two, as if it had taken sides between the two establishments.

The 'old' and 'new' towns were pretty much independent, with a mile's gap in between them. Aberdeen old town was a relic, an island in a rural landscape consisting of King's College itself, the old cathedral and accommodation for those who worked there. Marischal was located in the bigger and thriving new town. This had been rebuilt pretty much from scratch at the start of the nineteenth century, centred on the sweeping

Union Street, a 70-foot-wide boulevard to emphasise the solid worth of the granite city – so indeed it was very much a new town in Maxwell's day.

Though relatively small, Aberdeen had strong commercial roots, exporting a considerable amount of its trademark granite alongside textiles from the port, which also featured shipbuilders' yards. The newest addition in 1850, and something that opened up the city's trade even more, was the railway link, running down through Edinburgh to London, making Aberdeen far more attractive and accessible to a relatively cosmopolitan visitor like Maxwell.

By the time he was appointed, the religious divisions that had resulted in the setting up of the two separate universities were waning. Two years later, in 1858, Cambridge would finally drop the requirement for undergraduates to be members of the Church of England or its affiliates such as the Scottish Episcopal Church. Similarly, a Royal Commission had been set up as early as 1837 to look into the need for two separate universities in Aberdeen.

King's College was against a merger, but it was generally felt that the separate existence of King's and Marischal colleges was not beneficial to the education system in Scotland. Maxwell appears to have been aware of the situation, but not unduly worried. His immediate concern was finding somewhere to live in a city that he had probably never visited before. He took up lodgings with a Mrs Byers a few minutes' walk away from the college, his rooms reached via a quaint spiral staircase that took him above a law firm, J.D. Milne Advocates, at 129 Union Street, a location now featuring a string of familiar high street names from McDonald's to mobile phone shops.

Never a great enthusiast for college politics, Maxwell kept his head down and concentrated on his work as the in-fighting between the two universities continued. In fact, he noted in a letter to his aunt:

> I have been keeping up friendly relations with the King's College men, and they seem to be very friendly too. I have not received any rebukes yet from our men for so doing, but I find that families of some of our professors have no dealings, and never had, with those of the King's people.

In keeping with the scale of the city, the entire university that was Marischal was not much larger than an Oxbridge college, with twenty staff (fourteen professors and six lecturers) and 250 students enrolled when Maxwell arrived. It was an enviable position that involved a very short academic year, running only from November to April – so that the students were available back home on the farm or for seasonal work – leaving the staff with plenty of time to pursue their own research. For Maxwell this would mean the opportunity to spend half of his year at Glenlair, both working on natural philosophy and devoting his attention to the maintenance of the estate.

Although Maxwell was used to working in relative isolation when he was at Glenlair, it must have come as something of a shock to move from the vibrant atmosphere of Cambridge and the intellectual cut-and-thrust of the Apostles meetings to the academic backwater that Marischal represented. He had no doubt hoped to find the opportunity for the same mix of highbrow thought and enjoyable banter among his fellow academics, but the rest of the staff at Marischal proved to be much older than he was. It might not have been unheard of to make such young appointments in the universities of the day, but it certainly wasn't a Marischal tradition. The next closest in age of the other staff members was a 40-year-old, while the average age across Marischal's fellows and staff was 55.

This is not to say that Maxwell was made to feel unwelcome in his new post – quite the reverse. He was often invited out to dine with other staff members and seems to have been readily accepted into the fold – but it was inevitably a very different kind of environment from Cambridge. A letter Maxwell wrote to his school friend Lewis Campbell made it clear how things had changed: 'No jokes of any kind are understood here. I have not made one for 2 months and if I feel one coming on I shall bite my tongue.'

His lectures were terrible

There seems something of a dichotomy in regard to Maxwell's abilities as a professor in those early years. Like a number of other greats – Newton and Einstein, for example – he had some limitations as a lecturer. This was mentioned by friends such as Peter Tait, who would eventually remark in his obituary of Maxwell:

> [T]he rapidity of his thinking, which he could not control, was such as to destroy, except for the very highest class of students, the value of his lectures. His books and his written addresses (always gone over twice in MS.) 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.[†]

One of Maxwell's best students at Aberdeen, a David Gill,[‡] said that 'his lectures were terrible'. It seems from Gill's lecture notes that Maxwell prepared very clear, well-structured lectures, but had a tendency to diverge into anecdotes and analogies that left his students adrift – not helped by his lifelong tendency to make arithmetic errors. It was easy enough to correct these in his papers, but the slips he made during lectures made them something of an intellectual minefield.

It's worth considering, though, that most of the attendees at Maxwell's lectures in Aberdeen would have been very different from the students on a modern-day physics course. These were not scientific specialists – physics was just one of many topics covered on their four-year curriculum, which included everything from Greek and Latin to philosophy and logic. These students were probably of a reasonable calibre, as Marischal College was unusual for Scottish universities of the time in having an entrance exam and in only charging a relatively low fee of £5, with plenty of bursaries. This meant that around half of the students were from working families, who had won places on their merits.

Only in the third year would the natural sciences dominate for around 50 students. In his inaugural lecture, Maxwell emphasised that his course would require a shift of mindset:

> The work which lies before us this session is the study of Natural Philosophy. We are to be engaged during several months in the investigation of the laws which regulate the motion of matter. When we next assemble in this room we are to banish from our minds every idea except those which necessarily arise from the relations of Space, Time and Force. This day is the last on which we shall have time or liberty to deliberate on the arguments for or against this exclusive course of study, for, as soon as we engage on it, the doctrines of the science itself will claim our constant and undivided attention. I would therefore ask you seriously to consider whether you are prepared to devote yourself during this session to the study of the Physical Sciences, or whether you feel reluctant to leave behind you the humanizing pursuits of Philology and Ethics for a science of brute matter where the language is that of mathematics and the only law is the right of the strongest that might makes right.

It may have been that Maxwell's emphasis on mathematics (even allowing for an element of typical tongue-in-cheek phrasing), which he put more weight on than most of his contemporaries, was the reason his lecturing failed to endear him to many of his students. It's also worth stressing that Maxwell was limited by the standard approach to teaching science at the time, which would not have included any laboratory work. Given his lifelong dedication to experimenting, despite being primarily what we would now think of as a theoretical physicist, it's no surprise that he brought up the importance of experiment in that inaugural lecture:

> I ought now to tell you what my own opinion is with respect to the necessary truth of physical laws – whether I think them true only so far as experiment can be brought forward to prove them or whether I believe them to be true independent of experiment. On the answer which I give to this question will depend the whole method of treating the foundations of our science.
>
> I have no reason to believe that the human intellect is able to weave a system of physics out of its own resources without experimental labour. Whenever the attempt has been made it has resulted in an unnatural and self-contradictory mass of rubbish.[§] In fact unless we have something before us to theorize upon we immediately lose ourselves in that misty region from which I have just warned you.

The lack of practical opportunities for students in Aberdeen did not mean that Maxwell was limited to 'chalk and talk' in his lectures. Demonstrations were already well established both in public venues such as the Royal Institution in London and as part of physics teaching in universities. Maxwell would discover that Marischal's stock cupboard was well equipped with demonstration equipment, even if it was not always of the most up-to-date nature.

Despite any limitations in his presentation skills, Maxwell was a highly appreciated professor. He might not have yet developed the skills to put a lecture across well, but he was very hands-on and was ready to discuss scientific topics with anyone interested. The same David Gill who had called him a terrible lecturer also commented that Maxwell's teaching influenced the whole of his life. Students found that it was worth suffering his lectures if they then put in the effort to ask for more information. Maxwell also put on a voluntary advanced class for the fourth-year students – not part of the formal university teaching programme – which brought in the likes of Newton's laws, electricity and magnetism, topics that were considered too technical for most students. At the time, there was no honours degree available at Aberdeen, but Maxwell had instituted the intellectual equivalent for the physics course.

Lord of the rings

While in position at Marischal College, Maxwell demonstrated the breadth of his ability to think around a difficult problem by putting a considerable amount of effort into a challenge set by St John's College, Cambridge for its Adams Prize. This was a somewhat bizarre competition (still running) set up in honour of John Couch Adams, who had the misfortune to have produced a considerable amount of early data that suggested the existence of the planet Neptune, only to have his observations ignored, leaving the French co-discoverer of the planet, Le Verrier, to take the laurels.

The Adams Prize could, in principle, be set on any mathematical, astronomical or natural philosophy problem, but in the early years it was dominated by astronomical topics, not entirely surprisingly given that those in charge of the prize topic, George Airy and James Challis, were both astronomers. The challenges tended to involve so much work that the competition was not exactly over-subscribed. Maxwell entered to take on a topic set in 1855 that required hand-in of entries at the end of 1856 with results announced in 1857. This was the fourth time the prize challenge had been set – of the first three years, two had a single entrant, one had no entrants at all.

The topic for 1855 was the rings of Saturn, which, as we have seen, Maxwell had already started to work on during the summer vacation before heading off to Aberdeen. Ever since Galileo had seen something strange about the planet's appearance through his crude telescope and had drawn it as if it had jug-eared handles, assuming that what he saw was three stars that were lodged against each other, the rings had been a mystery. Apparently unique in the solar system (we now know that other gas giant planets have rings, though none is as dramatic as Saturn's), this structure seemed to defy nature.

The challenge was set out as follows:

> The problem may be treated on the supposition that the system of Rings is exactly, or very approximately, concentric with Saturn, and symmetrically disposed about the plane of his equator, and different hypotheses may be made respecting the physical constitution of the Rings. It may be supposed (1) that they are rigid; (2) that they are fluid or part aeriform; (3) that they consist of masses of matter not mutually coherent. The question will be considered to be answered by ascertaining, on these hypotheses severally, whether the conditions of mechanical stability are satisfied by the mutual attractions and motions of the Planet and the Rings.
>
> It is desirable that an attempt should also be made to determine on which of the above hypotheses the appearance of both of the bright rings and the recently discovered dark ring

> may be most satisfactorily explained; and to indicate any causes to which a change of form, such as is supposed from a comparison of modern with the earlier observations to have taken place, may be attributed.

Taken in isolation, the rings of Saturn provided an odd topic for Maxwell to work on. Although he did have wide interests in physics, he had never shown any great enthusiasm for astronomy beyond a youthful appreciation of the glories of the night sky from Glenlair, where a lack of street lighting had made for excellent star viewing. The same would be true for the rest of his career. It has been suggested that rather than reflecting the same kind of interest as he clearly had in colour, gases and electromagnetism, entering the competition was merely to take on the challenge of a puzzle to be solved, with the added bonus of a noteworthy prize attached.

Maxwell duly applied his mathematical expertise to the problem of the rings, an oddity that had challenged many of the greats. The first to recognise the rings as such, the Dutch scientist Christiaan Huygens, thought that they consisted of a single solid flat structure, but as telescopes became better able to resolve their detail it was increasingly clear that there were multiple rings surrounding the planet. The dark band that appeared to be a gap dividing two rings, referred to in the prize challenge, was first noticed in 1675 by Italian astronomer Giovanni Cassini, though strictly speaking the gap could have been a dark part of the same structure.

In 1787, French mathematician Pierre-Simon Laplace had got as far as demonstrating mathematically that the rings could not be continuous, symmetrical solid structures, as no material would be strong enough to prevent gravitational forces from ripping them apart. As Maxwell pointed out in his prize entry, iron, for example, would not only be plastic under the gravitational stress but would partially liquefy. Even if the rings rotated, which would partly counter the gravitational forces trying to tear them apart, the motion would fail to stabilise the situation, as such a model required inner parts of the ring to move faster than outer parts – the opposite of the reality of a single solid ring.

Instead, Laplace suggested that it was possible to make solid rings stable if the mass in them was unequally distributed. However, one of Maxwell's achievements in his Adams Prize entry was to show that, while Laplace was correct, the only stable structure would be like an engagement ring featuring an immense diamond, with 80 per cent of its mass concentrated on one spot. Such an uneven distribution of matter would have been clearly visible through the telescopes of the day. It just wasn’t the case.

Next, Maxwell considered the possibility that what appeared to be solid rings were in fact bands of liquid, a kind of space river that surrounded the planet. As he started work on the more complex mathematics involved in dealing with fluid dynamics, he wrote to his friend Lewis Campbell:

> I have been battering away at Saturn, returning to the charge every now and then. I have effected several breaches in the solid ring and now I am splash [*sic*] into the fluid one, amid a clash of symbols-[¶] truly astounding.

Here, Maxwell brought into play a mathematical tool that had been in use in an ad-hoc way for centuries, but had only been made generally applicable in the nineteenth century: Fourier analysis. The name refers to French mathematician Joseph Fourier, who in 1807, in a paper on the transfer of heat through solid bodies, showed that it was possible to break down any continuous function – effectively anything that could be represented on a continuous graph, however strangely shaped – into components that were simple, regularly repeating forms such as a sine wave.

It might seem unlikely but, for example, even a ‘jerky’ function such as a square wave can be broken down this way, provided we are allowed to use an infinite set of components to make it up exactly (see Figure 2).

Physicists and engineers now make use of Fourier analysis as a matter of course, but in Maxwell’s day the technique was still something of a novelty. Yet by using it, he showed that the way waves would combine should there be any disturbance in the rings (which would inevitably arise due to the gravitational attraction of Saturn’s moons and of Jupiter) made it impossible for a fluid to be as continuous as the rings appeared to be – they would simply not be stable, and the liquid or gas would accumulate in large globules. In effect if the rings were fluid, Saturn would end up with blobby moons.

With solid rings and fluids dismissed, Maxwell deduced that the rings were most likely collections of vast numbers of small particles, held in place by gravity – but that the distance between us and Saturn meant that we could not make out the individual particles, an analysis that has stood the test of time and close-up examination of the rings. His approach involved exploring the mathematics of displacements in a series of small satellites in the same orbit to see how waves caused by any disturbances could travel without breaking the ring apart.

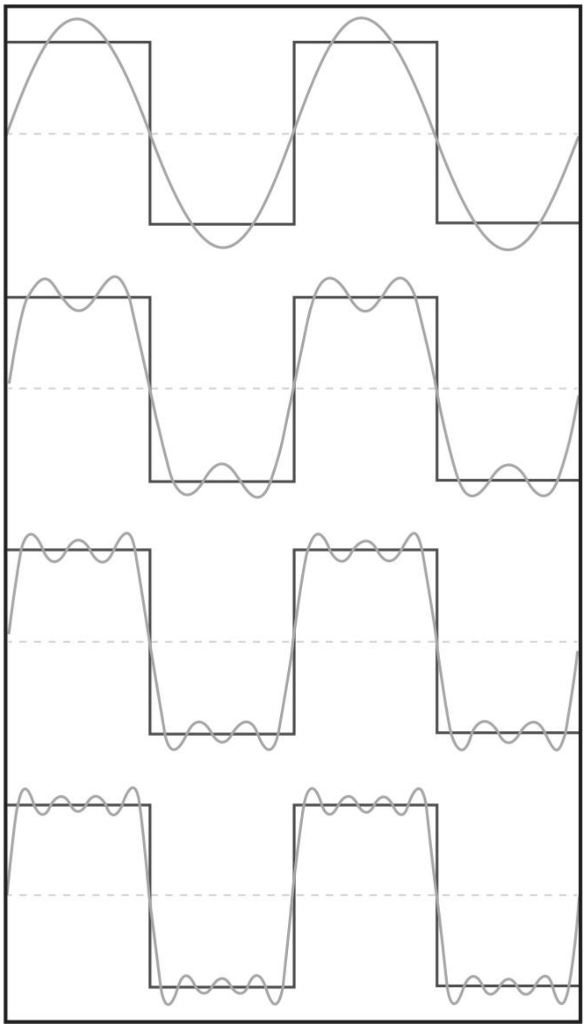

FIG. 2. *As more simple waves are added in, the result gets closer and closer to a square wave.*

Maxwell's conclusion: 'The final result, therefore, of the mechanical theory is, that the only system of rings which can exist is one composed of an indefinite number[||] of unconnected particles revolving around the planet with different velocities according to their respective distances.' Not only was this the only stable conclusion, in keeping with the second part of the question it was also the only one that could sensibly explain the multiple ring structure.

Maxwell began his essay with the words *'E pur si muove'* – the phrase that was allegedly, though almost certainly not, said by Galileo under his breath after recanting at his trial for heresy. Meaning 'And yet it does move', it seems a slightly odd choice in relation to the topic. Candidates were obliged to begin their essay with a motto, as a separate document linking the candidate's name to the motto was then used to preserve the anonymity of the essays until after the judging took place. It's possible Maxwell chose the words in honour of Galileo's discovery of the rings (or, at least, that Galileo noticed there was something odd about Saturn).

As it happens, the motto proved unnecessary. Maxwell's was the only entry that year and, not surprisingly, he won the prize. Astronomer Royal George Airy remarked that this was 'One of the most remarkable applications of Mathematics to Physics that I have ever seen'. Rather than just stop with his submitted essay, Maxwell took into account some comments made by the judging panel and developed his work as a background activity over the next few years, including having a mechanical model built by the Aberdeen-based instrument maker John Ramage, showing how waves could travel if the rings were made up of 36 satellites (made of ivory in the model). Obviously, reality would involve a far greater number, but the model demonstrated how fast-moving waves would be transmitted through the system. This was all before publishing the final version of his work.

Maxwell's prize entry may sound like an impressive but limited piece of work – the dynamics of the rings of Saturn appear to be something of a one-off application – but like many of his thought excursions throughout his working life, it would continue to have ramifications that went far beyond the initial use. The formation of planetary systems, such as our solar system, is a complex and not fully agreed problem to this day, but the best accepted theory depends on the accumulation of a disc of gas and dust, and this owes much to Maxwell's work on Saturn's rings. His achievement has been commemorated in a small way by naming a break in Saturn's C ring the 'Maxwell gap'.

This would not be the last time that Maxwell's unusual (for the day) combination of mathematics and physics would astound his contemporaries. It’s arguable that Maxwell was the most significant player in the transforming of physics into its modern form, from a largely descriptive discipline to one where mathematics began to drive progress in the field. It’s not that earlier physicists had ignored maths. Newton famously, for example, devised calculus so that he could perform his work on gravity. However, Maxwell took things further, moving from simply explaining observations through mathematics to building mathematical models that took on a life of their own.

Life in Aberdeen

Meanwhile, Maxwell was not content with his teaching work at the university and, much as he had been involved with the Working Men’s College at Cambridge, he gave an evening class as a contribution to the Aberdeen School of Science and Art. This was a body devoted to educating tradesmen and others with day jobs that prevented them from attending daytime lectures. As we have seen, this kind of paid evening education, often linked to bodies such as mechanics’ institutes, was common in the nineteenth century and helped many improve themselves. Students, who would typically already have worked for twelve hours from 6.00am, paid 8 shillings[**] a year for 24 lectures spread over five months from November to April. The School of Science and Art had no premises for Maxwell’s classes (though it was able to use the library of the Mechanics’ Institute), but he was allowed to give his lectures using the facilities at Marischal College.

It might seem that Maxwell had an overwhelming amount of work on, but he still found time for socialising, and for an activity that, as we have seen, he kept up throughout his life – writing verse. In 1857, Maxwell’s friend William Thomson was largely engaged with the laying of the transatlantic cable to send telegraph signals between the UK and the US. In a letter to Lewis Campbell, Maxwell noted that he had sent ‘great screeds’ to Thomson about Saturn’s rings, but it turned out that he was busy ‘a-laying of the telegraph which was to go to America’. In the process the cable broke. (According to Maxwell, this was because Thomson was ‘bringing his obtrusive science to bear upon the engineers, so that they broke the cable with not following (it appears) his advice’.)

Maxwell includes in his letter the words of a song he ‘conceived on the railway to Glasgow’. He notes that to avoid ‘vain repetitions’, ‘let (U) = “Under the sea”’, so that ‘2(U), by parity of reasoning, represents two repetitions of that sentiment’. The first two verses of ‘The Song of the Atlantic Telegraph Company’ (with an entertaining prefiguring of a song from Disney’s *The Little Mermaid*) read as follows:

2(U)
Mark how the telegraph motions to me,
2(U)
Signals are coming along,
With a wag, wag, wag;
The telegraph needle is vibrating free,
And every vibration is telling me
How they drag, drag, drag,
The telegraph cable along.

2(U)
No little signals are coming to me,
2(U)
Something has surely gone wrong,
And it’s broke, broke, broke;
What is the cause of it does not transpire,
But something has broken the telegraph wire
With a stroke, stroke, stroke,
Or else they’ve been pulling too strong.

Although Saturn had been an entertaining distraction, Maxwell had not abandoned the work on colour vision that he had started at Cambridge. His colour top to see the effect of combining different colours was useful, but it was relatively poorly calibrated. He was still writing papers based on it, as witness an enthusiastic letter from Michael Faraday, who wrote to Maxwell about receiving papers on the top and on Faraday’s lines of force:

> I have just read and thank you heartily for your papers. I intended to send you copies of two of mine. I think I have sent them, but do not find them ticked off. So I now send copies, not because they are assumed as deserving of your attention, but as a mark of my respect and desire to thank you in the best way that I can.

Receiving such a letter from one of his scientific heroes must have thrilled Maxwell.

At Aberdeen, however, he was to move beyond the colour top. With the help again of instrument maker John Ramage, he constructed a ‘light box’ in which adjustable-width slits could be used to vary the amount of each of the primary colours of light, beams of which were sent into a rectangular box where they were focused with a lens to produce a combined colour.

This was not just a matter of observing the behaviour of light – it also enabled Maxwell to continue his exploration of the nature of colour vision, and particularly the origins of colour blindness. In 1860, he would be awarded the highly prized Rumford Medal of the Royal Society for his work on colour vision, and he would continue working with light boxes in London after he left Aberdeen.

His achievements on Saturn and colours were undoubtedly small triumphs for Maxwell – but neither proved to be his most significant work while at Aberdeen, being little more than a pair of amusing diversions. Far more would rest on his development, starting in 1859, of the kinetic theory of gases. Although from the twentieth century onwards, Maxwell’s chief claim to fame would be his work on electromagnetism,[††] at the time of his death, his work on gases was seen as the highlight of his career, as the electromagnetic theory was not yet widely understood.

E pur si muove

The term ‘kinetic theory of gases’ is misleading. The theory has much to say about the nature of heat and of matter. It would be far more meaningful if it had been called the statistical theory of gases, not only because it has statistics at its heart, but also because it was the forerunner of the many ways that statistics would become fundamental to science. However, the ‘kinetic’ term was useful at the time to distinguish the new theory from the prevailing ‘static’ theory, which, rather than realising as we now do that molecules are zooming around and colliding, assumed that they sat around, busily repelling each other, producing the force of gas pressure from this mutual repulsion.

Statistics was originally a term for data about a country – it described a state, hence the name – but by the eighteenth century it was transformed by the gradual incorporation of the then new-fangled probability theory to become a mechanism for predicting behaviour of systems based on the likely behaviour of their components.[‡‡] And gases proved the ideal application for this approach. A gas had been regarded as a fuzzy elastic medium where the constituents somehow repelled each other so that the gas would fill the available space. But the German physicist Rudolf Clausius had started a new way of thinking about gases, regarding their behaviour as the result of the interplay of vast numbers of randomly moving, colliding bodies, which could only be treated statistically.

Statistics struggles with individuality[§§] or with systems that are chaotic, in the mathematical sense of having an interplay between highly interacting influences, resulting in large unpredictable variations over time as a result of small initial differences. But a gas is made up of large numbers of identically behaving components with no individual ‘personalities’ and only a small number of factors such as temperature and density influencing their behaviour, making it ideal for statistical analysis.

As far back as the eighteenth century, the mathematician Daniel Bernoulli had made the first use of statistical theory on gases, and in Maxwell’s time, for those who believed in atoms, many of the behaviours of gases were understood this way. We don’t know what a single molecule of gas is going to do. But we do know, given the many billions of molecules present in a room, how their behaviour will average out. And it had gradually been realised that their movement had something to do with heat.

Before Maxwell’s time there had been competing theories about the nature of heat. As we have seen, one approach described it as a kind of invisible fluid, ‘caloric’, that could move from one body to another. Much of the early work on heat engines and the conservation of energy was done using the caloric theory. But reflecting on the relationship of temperature and pressure in gases – and suspecting that pressure was due to the impact of gas molecules on the container – physicists began to suspect that caloric was an unnecessary complication, because what was being measured in reality was the energy with which the molecules that made up matter were jiggling about.

It was suggested by the developers of this new ‘thermodynamic’ theory, notably Clausius and Maxwell’s friend William Thomson, that temperature was a statistical measure of the energy of the molecules – the faster they move overall, the higher the temperature of the gas – while pressure reflected the impact from gas molecules hitting the walls of the container. But one of the behaviours of gas had yet to be explained using a statistical viewpoint (it would be left to Maxwell to take such a numerical approach) – this was the speed that a smell promulgated.

When a smelly substance – whether a perfume or something less pleasant – is released into the air, it takes some time for the odour to reach a distant nose. Yet at room temperature, gas molecules in the air should be flying around at hundreds of metres per second. So why do smells not arrive almost immediately? Clausius pointed out that the problem with the expectation of high-speed odour delivery was that the scent molecules did not have a free and easy journey from the source to the nose. There were vast numbers of air molecules in the way. The odour’s progress across a room would be a bit like attempting to take a straight-line stroll across the centre of a dodgems[¶¶] ride – you would soon be knocked over. Similarly, collisions of the scent molecules with other molecules would inevitably ensue, knocking the molecules in all sorts of different directions and slowing progress from A to B.

Imagine a single odour molecule from a newly brewed pot of coffee starting on its way across the kitchen. If there were no obstacles in its path, it could cross the few metres in a fraction of a second. But in reality, it may well undergo so many collisions and changes of direction that it would have to travel several kilometres before it reached the nose of a waiting breakfaster. Although Clausius deduced from this model that there should be an average distance a molecule travels between collisions (known as the mean free path), he was not able to calculate this distance, a value that would have enabled him to get a feel for the actual size of molecules.

Maxwell was intrigued by Clausius’ idea, but disliked the assumptions his rival had made. To make things simple, Clausius decided that it was acceptable to assume that all the molecules move at the same speed for a particular temperature. This certainly makes the mathematics easier to handle – but at the cost of losing the central statistical element of the theory and becoming totally unrealistic.

Temperature is not dependent on the speed (and hence kinetic energy) of an individual molecule, but on the *average* speed of the whole collection. Let's think specifically of that kitchen with its freshly brewed coffee pot. Some molecules in the air would have come into contact with the hot stove or with a windowsill heated by the Sun and as a result would be moving particularly quickly. Others would have given up energy as a result of contact with cooler matter and would have slowed down. There would be a whole distribution of different speeds and energies making up that average. Understanding the different probabilities involved was essential to developing a numerical analysis.

Statistics to the rescue

By bringing the statistics front and centre, Maxwell transformed the approach to the behaviour of gases. His was the first generation who could sensibly do so. Probability theory was only starting to be introduced in universities when Maxwell was an undergraduate. What had been a technique limited to considering games of chance[llll] and insurance premiums was increasingly seen as a tool that could be valuable in the physical sciences. For example, Maxwell's father's friend at Edinburgh, Professor James Forbes, had attempted to use probability theory to assess the likelihood that two stars, apparently very close to each other when seen through a telescope, were part of the same binary system, rather than simply happening to appear from the Earth to be situated in roughly the same direction.

Another eminent physicist of the day who became Maxwell's friend at Cambridge, George Stokes, the Lucasian Professor of Mathematics (a position held in their time by both Newton and Stephen Hawking), was responsible for some of the experimental data that Maxwell used in developing his 'dynamical' theory of gases. Maxwell notes:

> From Prof. Stokes's experiments on friction in air, it appears that the distance travelled by a particle between consecutive collisions is about 1/447,000 of an inch, the mean velocity being about 1505 feet per second; and therefore each particle makes 8,077,200,000 collisions per second.

We now refer to the ‘Maxwell distribution’ of speeds of molecules in gases, and his mathematical solution to provide the distribution of molecular speeds given a particular temperature is still used today. This was only the start of Maxwell’s pair of papers on the subject, to be published in 1860, which covered everything from the basics of pressure and thermal conductivity to viscosity and the way a gas diffused through different materials, seen from the molecular viewpoint.

His results on viscosity produced a particularly surprising outcome. Viscosity is a measure of the amount of drag a fluid presents to a body moving through it.*** The higher the viscosity, the more a gas (or liquid) resists movement. It had been assumed that the viscosity of a gas would increase with the gas’s pressure. Just as the gas pushes more on its container as pressure goes up, it seemed reasonable that it would push more on anything that tried to pass through it, slowing it down more.

But Maxwell’s theory suggested that viscosity should be independent of pressure. Admittedly there will be more molecules in the way at higher pressure – so you could imagine it’s the difference between wading through a full ball pool and one with just a few balls in it – but these molecules providing resistance to motion are also themselves moving. Maxwell’s calculations showed that the molecules’ ability to get out of the way of their fellows would counter exactly the extra quantity present in any particular volume. It would take a few years, but Maxwell would later demonstrate this experimentally.

Maxwell had made his first great contribution to physics – and one that at the time was given significantly more weight by many than his masterpiece on electromagnetic theory. Certainly, it was a topic that became something of a trademark for Maxwell. When a few years later he had attended a lecture at the Royal Institution in London and got wedged in a crowd trying to leave the lecture theatre, Michael Faraday was prompted to remark: ‘Ho, Maxwell, cannot you get out? If any man can find his way through a crowd, it should be you.’ This was a clear reference to Maxwell’s expertise on the paths of molecules.

The result of his analysis was not perfect. Maxwell had made a range of assumptions and at least one technical error, which would be pointed out by Clausius. And, as would remain the case throughout his career, his workings suffered from regular arithmetical slips. The German physicist Gustav Kirchhoff later commented: ‘He is a genius, but one has to check his calculations before one can accept them.' However, it seemed that Maxwell had reached as far as he wanted to go with molecules for the moment. He would return to kinetic theory, but not for several years.

A new family

The work that Maxwell was doing was unlikely to have gone unnoticed by the principal of Marischal College, the Reverend Daniel Dewar.[†††] Dewar was an interesting character who had risen from poverty. His father had been a blind fiddle player and Dewar spent his youth acting as his father's guide, porter and cash collector as they toured Scotland searching out the next gig. For whatever reason, Dewar was spotted by a rich benefactor as a youth with potential, paying for him to attend a private school.

Dewar went on to become a minister of the Church of Scotland. After he was appointed minister of the Greyfriars church in Aberdeen, associated with King's College, he came to the notice of the university and was elected Professor of Moral Philosophy there. Unfortunately, his rising fame as a preacher making him something close to a celebrity did not sit well with the college's idea of the decorum required of its professors. When Dewar would not resign from his ministry he was dismissed. He moved to Glasgow, where he took over the curiously named Tron church.[‡‡‡]

It was from this position that in 1832 Dewar was elected the principal of Marischal College. His was an external, Crown appointment and Dewar's humble origins and unseemly drive to succeed apparently did not go down well with the staff of the college, where it was noted snobbishly that he got the post with 'the unanimous disapproval of the College'. Yet, with time, Dewar's work ethic came to be appreciated, especially when he obtained funding for significant enhancement of the infrastructure, including construction of the impressive new granite main building.

Maxwell was a regular visitor to the principal's lodgings, a modest detached house (considering Dewar's role) at 13 Victoria Street West in Aberdeen. Although it is entirely possible that with such a small staff, Dewar would frequently expect to see Maxwell at his lodgings, it has been suggested that their first contact may have been over a book, *Gaelic*

Astronomy, by a teacher called D.M. Connell, the book itself written in Gaelic. Dewar had an interest in the language and had contributed to a Gaelic/English dictionary, so it may well have been a discussion of this 1856 work that first brought Maxwell to Victoria Street West.

At that time, Maxwell was 25, Dewar 71 and his wife Susan 60. Soon, the visits came to involve something more than a narrow discussion. Maxwell enjoyed covering a wide range of topics from theology and philosophy to literature and history with Dewar, a freedom of thought he had missed when moving from Cambridge to join the less socially minded Aberdeen fellows. And it was in the Victoria Street house that Maxwell met the Dewars' daughter Katherine Mary, one of seven children (though three had died and only one other, Katherine's younger brother Donald, lived at home).

Seven years older than Maxwell, Katherine was intrigued by his work and began to help with his colour experiments, making detailed observations as well as assisting with the practical side when Maxwell was caught up with theory. Maxwell became sufficiently close to the Dewars that he was asked to join them in September 1857 when the family took their annual break at a relative's home near Dunoon on Scotland's west coast. This holiday seems to have cemented the relationship: the following February, Maxwell proposed to Katherine.

He wrote to his aunt, Miss Cay:

> Dear Aunt, this comes to tell you that I am going to have a wife. I am not going to write out a catalogue of qualities, as I am not fit; but I can tell you that we are quite necessary to one another, and understand each other better than most couples I have seen. Don't be afraid; she is not mathematical; but there are other things besides that, and she certainly won't stop the mathematics.

The couple were married on 2 June 1858. Maxwell's lifelong correspondent and friend since school days Lewis Campbell was the best man (a reciprocal arrangement, as Maxwell had performed the same role for Campbell just a few weeks earlier down in Brighton). As well as supporting Maxwell's experiments in the sciences, Katherine also shared a wider range of interests with him, from literature and theology to walking and horse riding (though neither enjoyed any 'country sports' that involved killing animals). Though it appears Katherine was significantly less high-spirited than Maxwell, they were, without doubt, a well-matched couple, which would help greatly for the months of the year they would spend together in the relative isolation of Glenlair.

Accommodating the British Ass

During the first year of the Maxwells' marriage, it's likely that Maxwell had one thing foremost in his mind as far as work was concerned – the British Association for the Advancement of Science meeting. This organisation, usually contracted to BA, though Maxwell habitually referred to it as the British Ass, which is still going strong as the abbreviated British Science Association, had been started in 1831 as a way of improving the public understanding of science. Unlike the exclusive Royal Society, or the laboratory-centred Royal Institution, the BA was for the everyman and was specifically intended to have neither a building nor funds, but rather to provide pop-up events around the country to spread the scientific word.

After its founding, the BA put on a series of annual events, each of which lasted several days – effectively its annual meeting provided what would now be called a science festival. These gatherings attracted big crowds. Maxwell had been attending them regularly since the 1850 Edinburgh meeting, though he probably missed Dublin in 1857. The venue for a meeting was settled only a year in advance – and at the 1858 Leeds event (a meeting Maxwell had to miss due to his wedding), it was agreed that the 1859 meeting would be held in Aberdeen.

This no doubt thrilled Maxwell, but the only problem with the idea was that Aberdeen had no venue suitable for the large-scale lectures and discussions that were central to a BA meeting. Although the universities both had lecture theatres, and the more central Marischal College's main lecture theatre would be used for smaller side-events, they had nothing with the capacity required for the jamboree that the main BA meeting had become.

There had been talk for some time about building a music hall in Aberdeen, and the BA meeting provided a focus for making it happen. With Maxwell among its shareholders, the Music Hall Company set to work on the rapid construction of a spacious venue in Union Street. Almost inevitably constructed of granite, the imposing 50-foot-high internal space was capable of seating 2,400 and is still a major feature of the Aberdeen cityscape today.[§§§] The meeting, opened by Prince Albert, was a huge success.

Getting the Prince Consort along was a major feather in the organisers' caps. The location probably helped. Aberdeen might have been remote indeed from London, but it was handily located just 50 miles from one of Albert's pet projects, the Balmoral estate, where he had recently built a new castle, soon to be a favourite hideaway of Queen Victoria. In total, Maxwell gave three talks in the main venue – on his theory of gases, on colour theory, and on Saturn's rings.

Maxwell and the Prince were not the only attractions at a gathering that would see over 2,500 tickets sold. There were events ranging from a talk on the geology of northern Scotland to exhibitions of scientific instruments. One of the huge successes of the Royal Institution in London had been the public demonstrations – the flashier the better – and the BA event would not have disappointed with its displays of electrical discharges. It even seemed to get ahead of its time by demonstrating 'wireless telegraphy' before it had been invented – but although this term would later be applied to radio, the 1859 Aberdeen demonstration involved sending messages across the River Dee using the electrical conductivity of the water. Yet for all the 361 papers presented, there can be little doubt that by far the most significant for the history of science was Maxwell's first public outing of his 'Dynamical Theory of Gases' including his distribution for molecular velocities.

The exposure that Maxwell received at the BA meeting in Aberdeen made a wider section of the British scientific establishment aware of his capabilities, and it was well-timed, as his career was about to be put in jeopardy. His position as Regius Professor was one that traditionally would have been a post for life, had he desired it. Other young professors with similar positions – Thomson at Glasgow and Tait soon after at Edinburgh – would never move on in their careers. But Maxwell was soon to lose the only position he would ever hold in the Scottish academic system.

Leaving Aberdeen

During Maxwell and Katherine's engagement in 1858, the Universities (Scotland) Act was published, making it definite that Marischal College and King's College would be merged to form a single University of Aberdeen. The year after their wedding, it had become clear that Maxwell would be unable to stay in post. There was only to be a single chair of Natural Philosophy at the new united university, and this went to Maxwell's better-established rival from King's College, David Thomson (no relation to William).

All-in-all, after the successes of the previous two years, culminating in the British Association for the Advancement of Science meeting, 1860 began on a disastrous note for Maxwell. Not only did he lose his position because of the merger of the Aberdonian universities, he failed in his attempt to succeed James Forbes as Professor of Natural Philosophy at Edinburgh, a role that must have seemed ideal for Maxwell.

Here he was beaten by his old school friend Peter Tait (a fact that was hard to resent, though, as Maxwell had pipped Tait to the post to take the Marischal College position). This may seem an odd decision, given their relative publications; Tait had certainly not achieved anywhere near as much scientifically as Maxwell. It seems likely that the appointment was made because Tait was recognised as a significantly better lecturer, and the panel electing the professor, including William Gladstone,[¶¶¶] had limited scientific qualifications. An article by David Forfar and Chris Pritchard, comparing the work of Maxwell and Tait, comments:

> The evidence of Maxwell's superiority in research was, of course, already available to those with their eyes open. His investigation of the conditions required for the stability of Saturn's rings oozed originality. Yet, Thomson, Forbes, Stokes and Hopkins [English mathematician William Hopkins] merely resubmitted the testimonials in support of Maxwell which they had proffered to the authorities at Marischal College four years earlier and Faraday, as was his wont, declined to provide a reference at all. Only Airy drew attention to the fertility of Maxwell's theoretical astrophysics. As a body then his referees appear to have lapsed in shameful indolence or, more likely, failed to grasp the significance of Maxwell's work.

To make the year worse, Maxwell contracted smallpox, becoming dangerously ill over the summer. But once he had recovered, things finally began to look up. As well as publishing on the kinetic theory of gases, it was 1860 when his work on colour theory won him the Royal Society's Rumford Medal. He made another significant set of talks at the 1860 British Association for the Advancement of Science meeting, this year in Oxford, though his appearance was overshadowed by the now infamous debate over evolution between Bishop Samuel 'Soapy Sam'

Wilberforce and Thomas 'Darwin's bulldog' Huxley. Most significantly, two months after being turned down for Edinburgh, Maxwell finally gained a new position: the chair in Natural Philosophy (specifically dealing with physics and astronomy) at King's College London.

Newly married, Maxwell was about to move from the quiet and relatively rural Aberdeen to the largest, most dynamic city in Europe.

Notes

1 – Information on the Royal Commission from *Universities of Kings College and Marischal College, Aberdeen. First Report of the Commissioners, 1838* (1837–38), cited: http://gdl.cdlr.strath.ac.uk/haynin/haynin0509.htm

2 – Maxwell's letter to his aunt, Miss Cay, from 129 Union Street, Aberdeen, dated 27 February 1857, is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 263.

3 – Maxwell's letter to Lewis Campbell complaining of the lack of jokes at Marischal is quoted in J.J. Thomson's section of *James Clerk Maxwell: A Commemorative Volume 1831–1931* (Cambridge: Cambridge University Press, 1931), p. 13.

4 Peter Tait's explanation for Maxwell's poor lecturing is from Peter Tait, 'James Clerk Maxwell: Obituary', *Proceedings of the Royal Society of Edinburgh,* Vol. 10 (1878–80), 331–9.

5 – David Gill's opinion that Maxwell's lectures were terrible is taken from George Forbes, *David Gill: Man and Astronomer* (London: John Murray, 1916), p. 14.

6 – Maxwell's emphasis on mathematics and stress on the importance of experiment from his inaugural lecture at Marischal comes from Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), pp. 419–31.

7 – The wording of the Adams Prize topic is taken from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 505.

8 – The assertion that Maxwell only took on the rings of Saturn as an exercise in puzzle-solving is from Andrew Whitaker's contribution to Raymond Flood, Mark McCartney and Andrew Whitaker (eds.), *James Clerk Maxwell: Perspectives on his Life and Work* (Oxford: Oxford University Press, 2014), p. 116.

9 – Maxwell's letter describing his move from solid to liquid rings for Saturn is taken from Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 538.

10 – Maxwell's final statement on the nature of Saturn's rings is from James Clerk Maxwell, *On the Stability of the Motion of Saturn's Rings* (Cambridge: Macmillan and Company, 1859), p. 67.

11 – Maxwell's 'Song of the Atlantic Telegraph Company' is in a letter to Lewis Campbell from Ardhollow, Dunoon, dated 4 September 1857, quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 279.

12 – Faraday's letter to Maxwell on his papers is from Albemarle Street, London (location of the Royal Institution), dated 7 November 1857. It is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 288.

13 – Rudolf Peierls' remark about waking a physicist in the middle of the night is from Peierls' contribution, 'Field Theory Since Maxwell', to Cyril Dombe (ed.), *Clerk Maxwell and Modern Science* (London: The Athlone Press, 1963), p. 26.

14 – Maxwell's citing of George Stokes' results on gas particles is from 'On the Dynamical Theory of Gases', presented at the 29th meeting of the British Association for the Advancement of Science, held at Aberdeen in September 1859, reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), pp. 615–16.

15 – Faraday's remark that Maxwell should be able to find his way through a crowd is noted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 319.

16 – Kirchhoff's remark that Maxwell's calculations needed checking is frequently quoted, though I could not find an original source. It is quoted in this form in Robyn Arianrhod, *Einstein's Heroes: Imagining the World through the Language of Mathematics* (Oxford: Oxford University Press, 2006) p. 94.

17 – The Marischal College reaction to the appointment of Daniel Dewar is noted in P.J. Anderson, *Fasti Academiae Marsicallanae Aberdonensis,* Vol. II (Aberdeen: New Spalding Club, 1898), p. 30.

18 – The suggestion that the book *Gaelic Astronomy* brought Maxwell and Principal Dewar of Marischal College together is made by John Read in his chapter 'Maxwell at Aberdeen' for Raymond Flood, Mark McCartney and Andrew Whitaker (eds.), *James Clerk Maxwell: Perspectives on his Life and Work* (Oxford: Oxford University Press, 2014), p. 236.

19 – Maxwell's letter to Miss Cay from 129 Union Street, Aberdeen, dated 18 February 1858, is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 303.

20 – The article reflecting on Tait getting the job at Edinburgh over Maxwell is from David Forfar and Chris Pritchard, *The Remarkable Story of Maxwell and Tait,* accessed on the Clerk Maxwell Foundation website available at:
www.clerkmaxwellfoundation.org/Maxwell_and_TaitSMC24_1_2002.pdf

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[*] Admittedly all cities were smaller back in 1856, but compared with the largest city in the UK, London, at around 2.6 million, Aberdeen was still a minnow. It was only around half the size of the Lancashire mill town of Bolton at a similar date.

[†] This could be seen as a nasty put-down, but from Tait was clearly an affectionate assessment of his friend's original thinking combined with his difficulty of communicating ideas on the fly.

[‡] David Gill was the only one of Maxwell's Aberdeen students known to have become a scientist – he was later Queen's Astronomer at the Cape of Good Hope and became President of the Royal Astronomical Society.

[§] Some would say that this situation applies to certain aspects of modern physics, where theory often runs wild, unrestrained by experiment or observation.

[¶] Nice little pun there from Maxwell.

[||] This is sometimes reproduced as 'infinite number', but leaving aside the quibble that infinity isn't a number, Maxwell clearly was not thinking of there being an infinite set of particles.

[**] The equivalent of 40p, which would be around £36 now in monetary terms, or about £285 based on equivalent wages.

[††] Physicist Rudolf Peierls once said that ‘If you wake up a physicist in the middle of the night and say “Maxwell”, he will be sure to say “electromagnetic field”.’

[‡‡] Statistics in the modern sense was first practised by a button maker called John Graunt in London in the 1660s, and was developed in the coffee houses to become the foundation of the insurance business.

[§§] This is arguably why pollsters have had so much trouble with predicting the outcome of political events in the 21st century. Where once voters tended to behave as large, predictable blocks, they now tend to operate more individualistically, or in more complex groupings.

[¶¶] Bumper cars, if you prefer.

[||||] Bizarrely, the fact that probability was first devised to explain the best approach to betting and games of chance meant that in its early days it was considered a dark and dirty art. As far as a demon is concerned, that just made it all the more attractive.

[***] In effect, viscosity can be thought of as a measure of a fluid’s gloppiness.

[†††] Not to be confused with one of Maxwell’s contemporaries, another Scottish physicist who was associated with gases and temperature, James Dewar, who worked on low-temperature gases and invented the vacuum flask or ‘Thermos’ to keep them cool. You will find a statue to James Dewar outside the Buchanan Galleries shopping centre in Glasgow.

[‡‡‡] Nothing to do with the Disney movie. The Tron church (now the Tron Theatre) is located in Trongate, a street named after an old word for weighing scales.

[§§§] Entertainingly, the Musical Hall Company continued to attempt to send dividends from its proceeds to Maxwell at the (long defunct) Marischal College right through to the early 1900s, long after his death. The lawyers responsible for dealing with the payments eventually put an advertisement in the local paper asking for Mr James Clerk Maxwell to come forward, entirely unaware of either his fame or his death.

[¶¶¶] At the time Chancellor of the Exchequer and eight years later Prime Minister.

Demonic Interlude IV

In which the demon’s challenge is posed

When you look back at my creator in his early years, it can be hard not to consider him a touch of an oddball. It’s not that he was unsociable – which has proved a problem for many a scientist, in my experience. In fact, both at home in Glenlair and in Cambridge, JCM had enjoyed socialising and was known for his playful sense of humour. This often comes through in his letters, where he could be so mischievous it is sometimes difficult to make out what he meant. A highly technical letter to a fellow scientist could suddenly break out into a moment of whimsy, as when he remarked to his friend Peter Tait in something near text-speak: ‘O T′! R. U. AT ’OME?’*

Yet, back then, JCM was almost always to some degree an outsider. At Glenlair he had been the posh kid playing with the country yokels. He was himself a bumpkin when compared with his more sophisticated Edinburgh peers. He had been labelled as the uncouth student, accepted by Cambridge despite his personal characteristics. Did this outsider status help him develop his unique viewpoints? How should I know? I am a demon. But it’s hard to imagine that being an outsider wasn’t part of what made old JCM the way he was.

The other things that were already starting to have an influence on his path were the unexpected direction changes in his life. Just as he was really getting somewhere on electromagnetism, the lure of the new job in Aberdeen came along. And yet before he could make a start on that he also became laird of Glenlair. Many of his contemporaries put in a similar position would have packed in the university work and taken on the estate as their life. It’s not as if he needed the money. Science could have become a fulfilling hobby. It’s almost as if someone was trying to tempt him away from his true path. And it wouldn’t be the last time.

The tyranny of the second law

But enough about him – it's me you're interested in. It's my name on the front of the book. I'm going to be a trifle anachronistic here in the story of my maker's life. He would not conjure me up until eleven years after he had graduated from Cambridge. And when he did, he didn't have the decency to name me properly. He simply called me a 'finite being', I suppose meaning that I wasn't a god as I had limitations. As a name, it's a bit on the vague side, a term that could take in anything from an earthworm to a genius. As I've mentioned, it was his pal, that other dashing young Scottish natural philosophy professor of the high Victorian age, William Thomson, who realised my demonic nature.

Thomson, incidentally, got me all wrong. He claimed with a typical puritanical disdain for the interesting side of life that in calling me a demon he didn't intend me to be anything evil and inclined to temptation. No horns or pointy tail for his demon – he had in mind more of an intermediary, a spirit that was a kind of interface between the human and the divine. These days, he'd probably have spelt the word 'daemon' to emphasise the distinction. Sadly for humanity, old Thomson was wrong, though. Malevolence has proved to be very much my strong suit – I have always enjoyed getting human minds in a twist.

What is particularly satisfying is that I achieve this mental obfuscation with very little effort on my part. The role I was created for involves little more than opening and closing a door. But in doing so, I have a strangely satisfying role in the intriguing matter of disorder.

If you recall, we are dealing with the second law of thermodynamics, which could be summarised as 'Chaos is on the rise' (such a pleasant statement). Long-term, this has dire consequences for the universe as you know and love it. As JCM's frequent correspondent Thomson once put it: 'the end of this world as a habitation for man, or for any living creature or plant, at present existing in it is mechanically *inevitable* …' All thanks to my favourite law.

The second law says, then, that the level of disorder in a system stays the same or increases. And the system in question that I was introduced to control was ridiculously simple. Let's start by seeing the second law in action, unhampered. Imagine you've got a box of gas – air would do, but we'll make it pure nitrogen to keep things simple. The box is divided into two halves by a partition – on one side the gas is hot and on the other side the gas is cold.[‡] There is a door in the partition between the two sides which you leave open. What happens after a little time?

Molecules of gas from each side will randomly ping through the doorway. Some – the hot ones – will be travelling particularly fast. As we have seen, temperature is just a measure of the energy of the particles. The faster they travel, the more energy they have – the higher the temperature. Other molecules, the cold ones, will be relatively slow. So, we leave the door open for a good stretch of time. To begin with, most of the molecules leaving the hot side will be hot ones – and vice versa. So, the hot side will cool down and the cool side will heat up. Eventually the box will get to a state of equilibrium – each side will be around the same temperature. And the two halves should stay that way. We wouldn't expect to go back to a state where one side was hot and the other side was cold.

Notice, by the way, something that physicists forget at their peril. This whole business is purely statistical. It's entirely possible that for a fraction of a second all the molecules going one way might happen to be hot and all the molecules going the other way might be cold and the two halves of the box would reach different temperatures again. But it's very, very unlikely that this would happen for any significant period of time. We're talking about vast numbers of molecules. If my box was a metre cubed and the gas was at room temperature and pressure, there would be over 10 trillion trillion molecules in there. The chances of most of them acting in this way is very small – that's the statistical driver for the second law of thermodynamics.

As a little aside, the second law was originally conceived as a mechanical, unbreakable law that heat *always* moves from the hotter to the colder body, and it took some of our man Maxwell's contemporaries quite a while to come round to the statistical way of looking at things. JCM had his own rather nice way of describing what was involved: 'The 2nd law of thermodynamics has the same degree of truth as the statement that if you throw a tumblerful of water into the sea, you cannot get the same tumblerful out.' He was highlighting the fact that there is no absolute mechanical mechanism preventing the law being broken, it's just very, very unlikely.

What has all this got to do with the level of *disorder*? It's a bit of an odd term, but you can think of the difference between the two setups this way. When the hot and cold gases have mixed together, a molecule could be anywhere. But when they were separate, the hot molecules were on one side and the cold on the other. Then, we knew where to find the two different kind of molecules. There was more order in the system. It’s a bit like the difference between a page of this book as it now stands and the same page with all the letters scrambled up in any old order. The randomised page is not just useless as reading matter – it has more disorder. The second law is why it’s a lot easier to break an egg or a glass than it is to unbreak it.

The demon is summoned

So, we’ve got an idea of how the second law applies to a partitioned box. If the hot and cold gases did separate themselves spontaneously, that would break the second law. (Or to be precise, because the law is statistical, that would be very, very, very unlikely to happen according to the second law.) My role is to make that separation happen time and again with predictable ease.

What my creator did was to place me in charge of the door separating the two halves of the box. We start with the hot and cold molecules all mixed up. And then I simply open and close the door, depending on the kind of molecule that’s approaching it. If the molecule is fast, I only let it through if it’s travelling from left to right. If it’s slow, I only let it through going right to left. So, gradually, the hot and cold molecules separate. Order is produced from chaos and I break the second law. Neat, eh?

I seem to have first been mentioned in a letter written in 1867 to my creator’s friend Peter Tait, who was putting together a book on thermodynamics. JCM first described the box setup (calling the wall separating the halves of the box a ‘diaphragm’), then introduced me:

> Now conceive a finite being who knows the paths and velocities of all the molecules by simple inspection, but who can do no work[‡] except open and close a hole in the diaphragm by means of a slide without mass.
>
> Let him first observe the molecules in A [the hot side] and when he sees one coming the square of whose velocity is less than the mean square velocity of the molecules in B [the cold side] let him open the hole and let it go into B. Next, let him watch for a molecule of B, the square of whose velocity is greater than the mean square velocity in A, and when it comes to the hole, let him draw the slide and let it go into A, keeping the slide shut for all other molecules.
>
> Then the number of molecules in A and B are the same as at first, but the energy in A is increased and that of B is diminished, that is, the hot system has got hotter and the cold

> colder and yet no work has been done, only the intelligence of a very observant and neat-fingered being[§] has been employed.
>
> Or, in short, if heat is the motion of finite portions of matter and if we can apply tools to such portions of matter so as to deal with them separately, then we can take advantage of the different motions of different proportions to restore a uniformly hot system to unequal temperatures or to motions of large masses.
>
> Only we can't, not being clever enough.

In a letter to John Strutt (Lord Rayleigh) written three years later, JCM gave more detail about me, calling me 'a doorkeeper, very intelligent and exceedingly quick, with microscopic eyes but still an essentially finite being'.

In a later work, *Theory of Heat,* JCM made it clear that my role was to illustrate a wider range of possibilities, where 'delicate observations and experiments' would make it possible to take a look at the actions of a relatively small number of molecules, and in which case the familiar behaviour of vast numbers of molecules in a body would not be applicable.

It was four years after my first mention that William Thomson wrote a paper describing my efforts and cementing my fame, using the 'demon' word for the first time. He also set up a bizarre mental picture of a whole array of us demons bashing molecules with cricket bats, but this is far too undignified to give it any consideration.

Doing it without energy

Now, you may have spotted a slight flaw in the whole 'deployment of demons' business if you bothered to read one of the footnotes a way back. I pointed out that this experiment was a bit like an icebox in a warm room. Let's make it more specific. Let's make one half of the box a refrigerator and the other side the room it's in. We switch the fridge on and wait. After a while, the fridge side of the box is cold, while the other side is warm.[¶] A refrigerator in a room has achieved the same as I did, with no demons required.[‖] But there's a major difference between this picture and my effort.

The second law is restricted to closed systems, sealed off from the rest of the universe. The law only works if someone isn't pumping energy into the system. It's perfectly possible to produce more order from chaos if you work at doing so. Think of the Earth. You may consider nature to be fairly chaotic, but we see all kinds of structures that have formed over time – natural ones (including your body) and artificial ones. That wouldn't be possible without a vast amount of energy coming into the Earth to power it – and thankfully for you, the Sun provides as much energy as is needed and far more.

What made me special – particularly demonic, I guess you would say – is that I can do my business of sorting the thermodynamic sheep from the goats using the door without the need to put energy into the system. I am operating a frictionless, inertia-free door (not available at your local DIY store – this is a thought experiment) and no energy is added to the system by my actions. If you aren't comfortable with a frictionless door that has no mass, because that could never exist in the real world, bear in mind that this is just a convenience. The only essential as far the second law is concerned is that I do not put any energy into the system of molecules, which I don't.

So how do I perform my trick? How could someone, even with my unrivalled brilliance, break the unshakeable second law of thermodynamics? That was James Clerk Maxwell's challenge to the world – and himself. It's perhaps the only physics challenge he ever took on and failed at. As did his friends, like William Thomson. I was a conundrum. They couldn't see how it was possible for me do my job, yet equally they couldn't see why I would fail. Some people tried to argue that I was pointless – me, pointless! – because in the real world there couldn't be such a demon. But physics doesn't work like that. If a law's a law, it should hold up, whatever you throw at it. And I managed to beat it.

Or so it seemed back then, though I would have to face some challenges further on along the way. But I suppose we need to get back to my creator to see what happened when he ventured to the mighty metropolis that was London in 1860.

Notes

1 – Maxwell's postcard to Peter Tait from London, dated 23 October 1871, featuring 'O T'! R. U. AT 'OME?' is quoted in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 682.

2 – Thomson's statement that the second law made the end of the world inevitable is quoted in Stephen Brush, *The Kind of Motion We Call Heat: A History of Kinetic Theory in the 19th Century* (Amsterdam: North Holland, 1976), p. 569.

3 – Maxwell’s comparison of the second law to pouring a tumbler of water into the sea is from a letter to John Strutt (Lord Rayleigh), noted in Robert Strutt, *John William Strutt: Third Baron Rayleigh* (London: Edward Arnold, 1924), pp. 47–8.

4 – Maxwell’s first mention of the demon is in a letter to Peter Tait from Glenlair, dated 11 December 1867, reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 2 (Cambridge: Cambridge University Press, 1995), pp. 328–33.

5 – Maxwell’s description of the demon as intelligent and exceedingly quick was in a letter to John William Strutt from Glenlair, dated 6 December 1870, reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 2 (Cambridge: Cambridge University Press, 1995), pp. 582–3.

6 – William Thomson’s paper introducing the term ‘demon’ was William Thomson, ‘The Kinetic Theory of the Dissipation of Energy’, *Nature,* 9 (1874): 441–4.

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[*] In letters, JCM tended to refer to people by initials. T was already allocated to William Thomson, so Tait became T′.

[†] It may seem there is no imaginable reason for having such a box – and this is often the case in physicists’ thought experiments – but, as it happens, you could imagine this as a simplified version of putting an icebox into a warm room.

[‡] A little derogatory, I feel, that ‘who can do no work’. Perhaps it would have been better to have said, ‘who rightly felt that work was beneath him’.

[§] This is better.

[¶] The other side of the box is not just at room temperature – it warms up because the refrigerated side of the box has a radiator on the outside of it. Look at the back of any fridge.

[||] Assuming that refrigerator manufacturers, other than those in the fiction of Terry Pratchett, do not, in fact, employ demons as the operative part of their devices.

Chapter 4

A capital adventure

Every university that Maxwell had attended or worked at up until now was an ancient institution, still clinging on to traditions and even aspects of the syllabus that dated back to medieval times. But his new academic home, King's College, prestigiously located on London's Strand, took its first students only in the year that Maxwell was born (remarkably, before the 1820s, London did not have a single seat of higher education). The university's management prided itself on its modern values, with explicit courses in individual scientific disciplines, rather than traditional, classical-heavy, 'bit of everything' undergraduate courses; they even covered the upstart, hands-dirty topic of engineering.

Science at King's

We can get a feel for Maxwell's attitude to science and how it should be approached from part of his stirring inaugural lecture at King's. He told the students:

> In this class I hope you will learn not merely results or formulae applicable to cases that may possibly occur in our practice afterwards, but the principles on which those formulae depend, and without which the formulae are merely mental rubbish. I know the tendency of the human mind is to do anything rather than think. But mental labour is not thought, and those who have with labour acquired the habit of application, often find it much easier to get up a formula than to master the principle.

Maxwell was emphasising the importance of doing more than ticking the boxes and mechanically working the equations – as we now might allow a computer to do for us. His approach to science was always to look for underlying principles, to get as close as he could to the true 'laws' of nature.[*] To get a flavour of the duties expected of him, Maxwell was required to be in college three mornings a week (10.00am to 1.00pm) and to give one evening class aimed at working men – leaving a comfortable amount of time for working on his own projects.

His pay from the university was directly linked to the number of students he taught, receiving 5 guineas (£5.25) for each day student, 18 shillings (90p) for each evening class student and £2, 7 shillings and threepence (just over £2.36) for each ‘occasional student’, who did not matriculate but were enrolled in individual classes to gain expertise. This made him around £450 a year, the equivalent of around £39,000 now,[‡] a little more than he had earned in Aberdeen. In practice, though, he was significantly better off, as one of the conditions of the Aberdeen merger was that he would receive a remarkably generous annuity for life of his salary when he lost his position, giving him an additional £400 a year, making his annual income a handsome £850 – around £76,000 in purchasing power or £579,000 in proportion to earnings.

Something of Maxwell’s approach to teaching while at King’s College can be seen in an incident recorded in the Campbell and Garnett biography written shortly after his death:

> The professors had unlimited access to the [College] library, and were in the habit of sometimes taking out a book for 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.

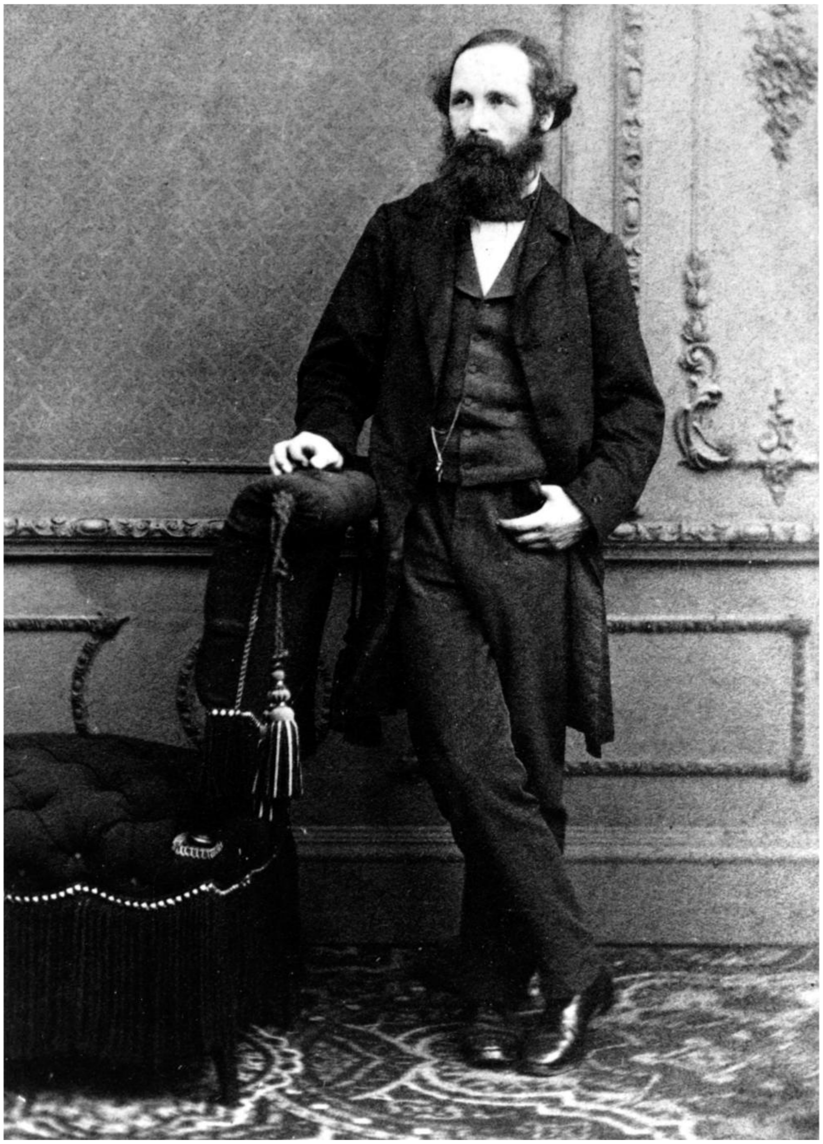
While this early biography has a tendency to paint Maxwell in something of a saintly light, it illustrates here an unusual attitude for a professor at the time and perhaps reflects both Maxwell’s youth – at 29, he was still only a few years older than his students – and his unusual upbringing for someone of his class, having mixed with the working class far more than would be the norm for the landed gentry.

The students Maxwell taught at King’s College had a strong focus on practical, applied science – many of the young men in his physics and astronomy classes would become engineers, a subject that was hardly recognised at other universities, and they received training that would benefit them in such roles. This meant that their education was seen as more of a boost to their practical skills than a means of obtaining a degree,[‡] and the majority did not stay for a complete three-year course, typically averaging just over four terms before moving on. The fees at King’s were over seven times those of Marischal College at £12, 17 shillings (£12.85) for each of the three terms, though those wanting only to attend natural philosophy classes had a cut-price rate of just 3 guineas (£3.15) a term.

Maxwell and Katherine had a comfortable home to entertain guests at 8 Palace Gardens Terrace in Kensington (oddly, this is now number 16). It was a fair walk to reach the Strand, though Maxwell often would, when he wanted to exercise his country-bred legs with a four-mile stroll. The house may well have reminded him of his aunts' houses in Edinburgh – Palace Gardens was a little grander, with five storeys and pillars at the entrance, but it was still a solid city townhouse.

After Aberdeen's relative social backwater, Maxwell was looking forward to having more opportunity to meet with like-minded individuals, as had been possible in Edinburgh and Cambridge. Where the entire staff of Marischal College dealing with all disciplines numbered just twenty, Maxwell's department of Applied Science alone, one of four at King's College, had a similar number. And his colleagues were only the start.

Both the Royal Society and its more practically-minded little brother, the Royal Institution, offered lectures and discussions in the city attended by many of the leaders of British science – and in May 1861, Maxwell was thrust to the fore with an invitation to give a lecture at the Royal Institution (RI).



Maxwell in the 1860s, during his post at King's College London or shortly afterwards.
Getty Images

Bring colour to the Institution

The RI was the spiritual home of Maxwell's hero, Michael Faraday. As we have seen, Faraday started at the Institution as an assistant to Humphry Davy and now, though 70, Faraday was still associated with the venue where he had given so many lectures and set up the famous Christmas Lecture series for children. Following on from his Rumford Medal, Maxwell was asked to give a lecture at the RI on colour theory, a topic that would remain a lifetime interest for him.

One of the traditions of the Institution was to give demonstrations during lectures – the more dramatic presentations were popular draws, sometimes bringing in royalty among the audience. The spinning colour wheel that Maxwell had used in his experiments was too small for the audience to see it at a distance, so he decided to produce something that had never been seen before – he would project a large-scale image of a true colour photograph.

It was common enough for black and white photographs to be hand-tinted to give the effect of colour, but Maxwell's plan was to produce a full colour image by combining three monochrome photographs taken and then projected using red, green and blue filters, demonstrating that these three primary colours were sufficient to generate all the colours that we see. He had first conceived this idea back in 1855, when he had briefly discussed it at the Royal Society of Edinburgh, but in the best manner of Royal Institution demonstrations, he intended to bring the theory alive before his audience.

Maxwell was no photographer himself – at the time, a distinctly specialist activity. But luckily, one of the country's top experts, Thomas Sutton, himself a Cambridge Wrangler in his day, had been employed as the official King's College photographer, a role that was primarily a teaching one. Sutton was able to help Maxwell with the tricky (and potentially dangerous) photographic medium of wet collodion. This was no simple matter of buying a roll of film and having it processed, let alone the ease of modern digital photography. The photographer had to be a deft chemist before there was any possibility of taking an exposure.

The wet collodion process started with cotton being soaked in a toxic and highly corrosive mixture of nitric and sulfuric acids. The product – gun cotton[§] – had to be washed and dried before dissolving it in ether or alcohol to produce a terrifyingly flammable gel. The would-be photographer then added halogen salts (iodine or bromine) to the gel and spread the resultant suspension carefully onto a clean glass plate. This part of the process required particular skill to get a consistent, level layer of the 'collodion' gel. The plate was then dipped in a bath of silver nitrate, which reacted with the halogen to produce a light-sensitive silver-based coating. After this 'activation' process, the plate, still wet, was placed in the camera and exposed. Finally, the plate had to be developed, fixed, rinsed, dried and varnished before the final product was available. This was anything but ‘point and shoot’.

Under Maxwell’s direction, Sutton took three separate photographs of a multicoloured tartan-like ribbon,[¶] using red, blue and green filters, made by mixing different coloured dyes in water and placing the camera behind glass troughs containing the liquids. Maxwell was then able to superimpose the three separate images projected onto a large screen at the RI with three magic lanterns, each shining through one of the red, blue and green troughs.

Making it happen on the night must have given Maxwell some bitten fingernails. His talk was a Friday Night Discourse, the most fearsome of Faraday’s public event programme. The audience were a stern mass of black ties and the speaker was required (as they still are) to crash through the doors of the lecture theatre on the second of the starting time and begin speaking immediately without introduction. But everything went well; Maxwell pronounced himself satisfied with the outcome. The three light beams combined on the screen to give a relatively realistic-looking colour image of the ribbon,[‖] though Maxwell did remark that a better result could be obtained with materials that were more sensitive to colours away from the blue end of the spectrum.

It was a few weeks later in May 1861, still only 29, that Maxwell was elected a Fellow of the Royal Society, cementing his position as a member of the London scientific establishment. In the present day, election to a fellowship of the ‘Royal’ is probably the highest honour available to a British scientist, though in the Society’s early days, most fellows weren’t scientists per se, but rather wealthy individuals who had an interest in science. By Maxwell’s time the shift in the membership to actual scientists was well under way, though he would have qualified on both counts.

Electromagnetism goes mechanical

By the time of his Royal Institution lecture, around five years had passed since Maxwell had last worked on electromagnetism. Whether inspired by appearing at Faraday’s lecture table or simply coming naturally back to a topic that would always fascinate him, while at King’s College he picked up the subject where he had earlier left off. His previous model, treating electricity and magnetism as fluids, was workable only for fields that did not move. But to cope with the likes of generators and electric motors, now becoming relatively common as a result of Faraday's work, Maxwell had to deal with movement. Just as he had transformed his picture of the rings of Saturn from solid to fluid to particles, he now modified his approach to electromagnetism by resorting to a mechanical model.

This 'model', like many that physicists would construct from Maxwell's time to the present day, was not a model in the sense of a small-scale physical construction, looking like the real thing. Instead he used a theoretical construct that reflected what was observed in nature and that could be used to make predictions to see whether the model was an effective representation of the phenomenon, or whether it needed refining. This was not an actual mechanical device, but one that used the principles of mechanics to try to reproduce the effects of electromagnetism.

Electromagnetism has one fundamental difference from the other force of nature that we experience directly – gravity. All gravity attracts.[**] But electromagnetism comes in two flavours, known as negative and positive for electricity, and as north and south for magnetism. The rule is that like flavours (say negative and negative for electricity, or south and south for magnets) repel while opposite flavours (negative and positive, or north and south) attract. Bring together electrical charges or magnetic poles and this becomes very obvious. Maxwell set out to model this process, starting with magnetic poles, using a model of the magnetic field that worked in a purely mechanical fashion.

There are a couple of other requirements he needed to cope with in designing a model to work for magnetic poles. One is that they always seem to come in opposing pairs – unlike electrical charges which are happy to be standalone negative or positive, we have never seen a separate north or south pole[††] – and the force that is felt between poles, whether repulsive or attractive, obeys an inverse square law as does gravity, dropping off at the same rate as the square of the distance between the two poles that are attracting or repelling each other.

The biggest problem that Maxwell faced was the same one that had caused many to struggle in trying to find a model to explain how gravity could work. It’s relatively easy to have a mechanical model that produces the effect of repulsion, because it’s easy for one object to push another. But it’s harder to have a model that produces attraction, as without involving something like magnetism it’s difficult to see how one object can pull another to which it has no direct physical connection.

Ever since Newton’s time this problem had been got around by devising mechanical models for gravitational attraction which were based on the idea that space was filled with invisible high-speed particles heading in all directions which did not interact with each other, but which pushed on massive bodies. Usually the impact from all directions balanced out, but when a second body was nearby, it blocked some of the particles heading towards the first body, producing the effect of attracting one body towards the other. These models needed a fair amount of tweaking, as the obvious implication is that gravitational pull would depend on the size of a body rather than its mass. There seems no evidence that Maxwell ever considered this type of model for electromagnetic attraction.

Maxwell’s electromagnetic spheres

Maxwell’s first attempt with his mechanical model was to imagine that the magnetic field was made up of a collection of spheres,[‡‡] tightly packed to fill space. These spheres or ‘cells’ would be spinning around. Generally speaking, when a physical object spins, the centrifugal forces[§§] acting on it make it spread out in the middle and contract at the poles. This happens, for example, to the Earth, which it had been known since Newton’s time has a bulge around the equator and so is an oblate spheroid rather than a perfect sphere.

But, unlike the Earth, Maxwell’s spheres were surrounded by other spheres. So, if the equator of a sphere expanded as it was spinning, it would push on the surrounding spheres. In this model, the axes of the spins were aligned to the lines of force that Faraday had demonstrated in the magnetic field. The result would be very close to what was observed. At right angles to the lines of force – the direction of the equators – the forcing outwards of the spheres would produce a repulsive effect, while along the lines of force – the direction of the poles – the spheres would be pushed closer together and the effect would be an attraction.

Conveniently, the faster the spheres rotated, the bigger this effect would be – so the spin rate in the model corresponded to the strength of the magnetic field. In this kind of mechanical model, it's perfectly possible for the components to be allowed to be frictionless, but Maxwell thought it better to allow for a degree of interaction between the spheres. If two spheres alongside each other are turning in the same direction, then at the point of contact, the surfaces will be moving in opposite directions.

If you imagine two spheres, moving clockwise, with their axes pointing out of the page, the left sphere's surface moves down at the point of contact while the right sphere's surface moves upwards (Figure 3).

To avoid direct interaction between the spheres, Maxwell imagined a large number of much smaller spheres acting like ball bearings between the main spheres. But unlike the ball bearings in a traditional device, which are usually constrained by a bearing, these would be free to flow as they like. And if these little spheres were considered as particles of electricity (what we'd now call electrons), when an electrical circuit was made, the little spheres would flow in the channels between the bigger ones. (Let's call the bigger spheres cells, as Maxwell did, to avoid getting our assorted spheres confused.)

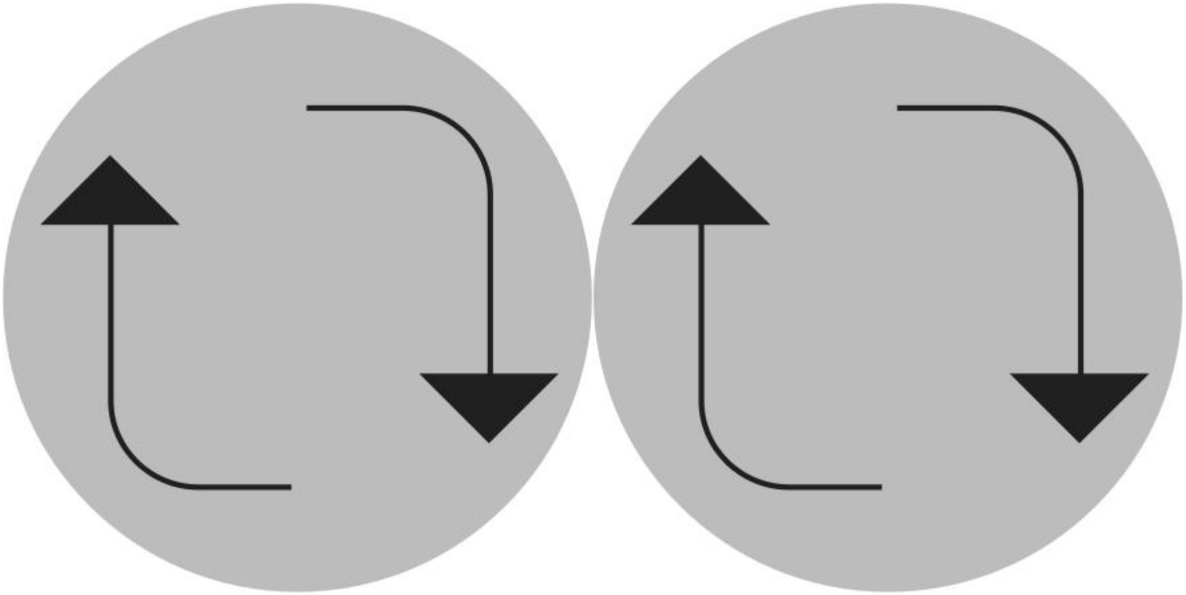


FIG. 3. *Two spheres rotating in contact.*

What’s particularly neat about this model is that we now have an interaction between electricity (little spheres) and magnetism (cells). If an electrical current flows, the result is that the cells start to rotate and a magnetic field is produced.

Maxwell was also able to extend the model to allow for different materials – the better the conductor, the more easily the spheres were able to flow. In an insulator, the magnetic cells clung onto the little electrical spheres sufficiently that it was very hard to get any electrical current. So now his model dealt with the difference between insulators and conductors as well as electromagnets. But this was not all there was to electromagnetism. He would also have to cope with induction.

As we have seen, this was something that Faraday had investigated. He had shown that a changing magnetic field would produce a flow of electricity – this was how electrical generators worked. Induction also occurs when a current is started in a wire that is near another wire. When the electricity is switched on it produces a magnetic field. As far as the other wire is concerned, to begin with there is no magnetic field, then one surges into place and becomes steady. As the field is established there is a changing magnetic field, so a blip of current flows briefly in the second wire. The same thing happens if the first wire’s current is switched off.[¶¶]

Vortices and idle wheels

By now, as Maxwell refined the model, his cells had become hexagons, which made the model clearer visually. His original diagram had rather more hexagons than are necessary to make the point, but we can envisage what he had in mind with just three rows of hexagons. I am indebted to Basil Mahon for the following neat representation of Maxwell’s reasoning. The row of tiny spheres[||||] between the top cells and the middle row is connected to a loop of wire – this is where the induction will take place. And the row of spheres between the middle row and the bottom row of cells is connected to a wire with a battery and a switch. We are ready to induce some current.

The experiment starts in the state of diagram I in Figure 4. The switch is yet to be thrown so there is no electrical current flowing.

After the switch is thrown, in diagram II, the spheres start to flow left to right between the middle and bottom sets of cells. The middle cells begin to rotate in the opposite direction to the bottom row. Maxwell had identified the direction of the magnetic field as the direction of rotation in his model, so the magnetic field above and below the electrical current flowing is in opposite directions – it is circling around the wire.

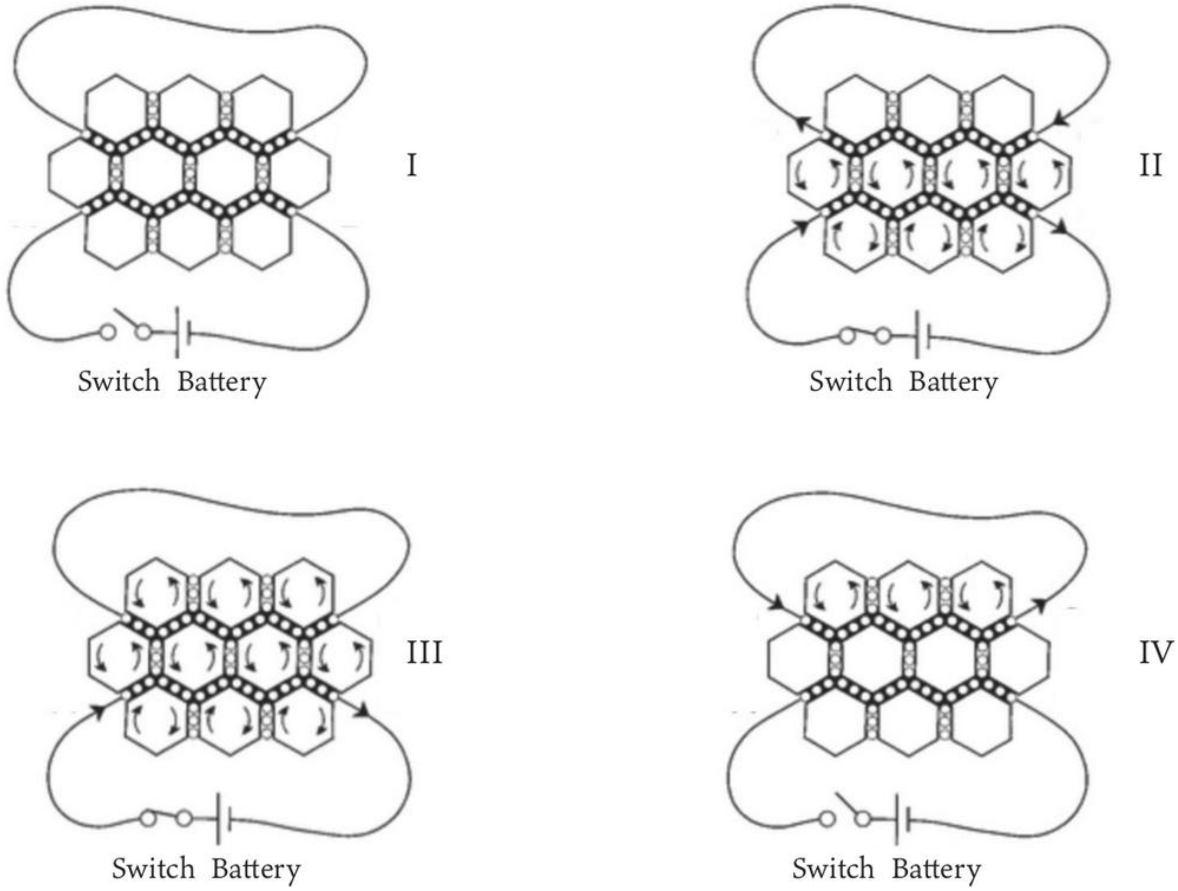


FIG. 4. *Maxwell's mechanical model of electromagnetism.*

Meanwhile, the spheres between the top and middle cells are being pushed by the rotating cells in the middle row. These little spheres start to rotate clockwise and to flow right to left, causing a brief current in the upper wire. However, there is no battery in this circuit to keep the current flowing. The resistance in the wire slows the spheres down until they stop moving, but they are still rotating clockwise. This rotation causes the upper row of cells to rotate in the same direction as the middle row, as in diagram III.

When the switch is opened (diagram IV), the bottom flow of spheres rapidly stops, slowing the bottom and middle rows of cells. But the top row is still rotating – the rotating cells act as tiny flywheels, enabling the ether (see below) to briefly store energy which then generates another brief flow of current in the top wire before the whole system settles down to stillness.

By this stage Maxwell's remarkable and very Victorian feeling model[***] had explained three of the main aspects of electromagnetism, though he had not yet managed to incorporate the attraction and repulsion between electrical charges. If you feel that this construction of arbitrary mechanical components seems a little unlikely – too far abstracted from reality to be useful – you are not alone. The French physicist Henri Poincaré remarked that there was a 'feeling of discomfort and even of mistrust' among his fellow countrymen when faced with Maxwell's mechanism. This was taking a model, a mechanical analogy of reality, and stretching it to what seemed to him a ludicrous extreme. And yet it was working.

The power of analogy

For, Maxwell, this novel use of analogy – building models – was the way forward to better understand the physical principles of the natural world. While still a student at Cambridge, he had written:

> Whenever [men] see a relation between two things they know well, and think they see there must be a similar relation between things less known, they reason from one to the other. This supposes that, although pairs of things may differ widely from each other, the *relation* in the one pair may be the same as that in the other. Now, as in a scientific point of view the *relation* is the most important thing to know, a knowledge of the one thing leads us a long way towards knowledge of the other.

… and this philosophy, initially based on mechanical and later on purely mathematical models, would be the key to his remarkable success.

It was relatively easy to see how Maxwell's earlier model of fluid flows through a porous medium had come about from the influence of Thomson's work on heat, but this far more sophisticated model seems to have come out of nowhere. However, Maxwell was very fond of having actual mechanical models built – think, for example, of his colour top, or the mechanical model he had made to illustrate waves in the rings of Saturn.

At the same time, he was now in London, where Charles Babbage had dreamed up his remarkable mechanical computers, the difference engine and the analytical engine. Though neither was built, Babbage had completed a working model of part of the difference engine and had worked, with the help of Ada, Countess of Lovelace, on the principles of the far more sophisticated analytical engine. Babbage was still alive when Maxwell spent his time in London. It is surely likely that it was the experience of the many brass miracles of Victorian engineering that led Maxwell to his remarkable hexagons and ball structure.

What is certainly without doubt is that Maxwell's electromagnetic model proved surprisingly flexible, given its nature. For example, different materials vary widely in their magnetic properties. Even between metals, the differences are stark, and when you bring in other materials, such as wood, it's clear that there is a major difference in the way magnetism operates (or doesn't) between different substances.

What Maxwell had constructed was a mechanical model of the ether, the fluid that was thought to fill all space, allowing light waves to pass through a vacuum and acting as the transmission mechanism for the electrical and magnetic fields. What he suggested was that when that ether was overlaid on different materials the result would be a change in the nature of the hexagonal cells in the model. The better the magnetic properties of the material, the more dense was the cell in the model. With increasing density, the cells would produce a greater centrifugal force, producing more magnetic flux – the measure of the strength of the magnetic field.

In building this model, we need to reiterate, Maxwell did not suggest that space was full of rotating hexagonal cells and tiny ball bearings – not even invisible cells and bearings – but rather he was suggesting that the way the ether behaved produced a result that had the same effect as his imagined mechanical structures. There was, however, a big difference between this new model and his original fluid idea. Although Maxwell *did* not see the exact detail of the model with its ball bearings and hexagonal cells as what was actually happening in the ether, he did think that he had now come much closer to reality. There seems little doubt that his thoughts on what was *really* happening were influenced by William Thomson, who had firmly stated that there were actual vortices in the magnetic field, reflected in the way that the magnetic field influenced light.

Maxwell never lost his belief in the existence of the ether,[†††] a substance that would be thrown into doubt by an experiment carried out by the American scientists Albert Michelson and Edward Morley in 1887 and eventually dismissed altogether by Einstein’s work at the start of the twentieth century. And Maxwell did think that the magnetic field involved actual rotating vortices in that invisible, undetectable medium. The ball bearings part of the model proved more of an embarrassment.

Maxwell commented that ‘The conception of a particle having its motion connected with that of a vortex by perfect rolling contact may appear somewhat awkward. I do not bring it forward as a mode of connexion existing in nature …’ On the other hand, he points out that it works well and as long as it is taken as provisional and temporary, it should help rather than hinder a search for the true interpretation of the phenomena.

So, Maxwell was making it clear that the ether is not a matter of having space full of hexagons and ball bearings, any more than the crystal spheres of the ancient view of the universe. Even so, the ether had to be a remarkable substance indeed. It was invisible, impossible to detect, yet provided the medium for light to wave through, and was elastic, as it would have to be for waves to pass through it, but was somehow also so rigid that light could continue to travel for vast distances, seemingly without losing any energy the way that a conventional mechanical wave would. The ether was such a firmly established part of scientists’ mental model of reality that it was extremely hard to shake off.[‡‡‡] For Maxwell, the specific details of his model provided an effective mechanical analogy for a more complex fluid reality.

He therefore tried to measure the effects of the vortices in the ether directly by having a device built that involved a small electromagnet free to rotate in all three dimensions; this, he hoped, would detect the impact of nearby vortices. Nothing was discovered, which merely underlined for him that the vortices appeared to be very small. Similarly, he believed that the electric field was directly linked to elastic deformation of the ether – again, he was not saying that his specific model was an accurate portrayal of reality, but that the key features, such as vortices and the elastic response, were a reflection of reality and so should have the kind of impact we would expect the components of the model to produce.

This belief of Maxwell's in what we now know not to exist should not be used to belittle his achievements – it was a perfectly reasonable possibility at the time. But it also illustrates that he was only part-way towards the acceptance of a model as something totally isolated from the reality it reflected, which would enable the eventual development of purely mathematical models that have come to dominate physics.

There was no doubt that, at King's College, Maxwell had begun to really make something of the insights that drove him. He published his findings in a two-part paper. His original work on electromagnetism had been called *On Faraday's Lines of Force* – the new paper was *On Physical Lines of Force,* emphasising that he had moved on to a more practical model. It was published in *Philosophical Magazine,*[§§§] with Part 1 in the March 1861 edition and Part 2 split between the April and May editions.

Notes

1 – The extract from Maxwell's inaugural lecture is taken from Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell,* Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 671.

2 – The description of Maxwell borrowing books from the King's College library for his students is from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 177.

3 – The description of the wet collodion photographic process is taken from Brian Clegg, *The Man Who Stopped Time* (Washington, DC: Joseph Henry Press, 2007), p. 34.

4 – The representation of Maxwell's reasoning here, using four sequential diagrams, is adapted from Basil Mahon, *The Man Who Changed Everything: The Life of James Clerk Maxwell* (Chichester: Wiley, 2003) pp. 100–03.

5 – Poincaré's observation of his contemporaries' mistrust for Maxwell's mechanical model is from John Heilbron, 'Lectures on the history of atomic physics 1900–1922', in *History of twentieth century physics: 57th Varenna International School of Physics, 'Enrico Fermi'* (New York: Academic Press, 1977), pp. 40–108.

6 – Maxwell's remarks on the benefit of analogy are taken from James Clerk Maxwell, 'Analogies in nature' (1856), in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 1 (Cambridge: Cambridge University Press, 1990) pp. 376–83.

7 – William Thomson's assertions that vortices existed in the magnetic field are made in William Thomson, 'Dynamical Illustrations of the Magnetic and Helicoidal Rotatory Effects of Transparent Bodies on Polarized Light', *Proceedings of the Royal Society* (1856), 8: 150–58.

8 – Maxwell's admission that the ball bearings in his model were 'awkward' is from William Davidson Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, Vol. 1 (Cambridge: Cambridge University Press, 1890), p. 486.

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[*] The concept of a natural law is rather an elusive one. Laws are written down in black and white. A natural law is more an analogy of what nature is like, as we can arguably never directly interact with reality, merely observe phenomena. But that's all too philosophical for me – there's a special breed of demons who specialise in philosophy.

[†] Calculating present value of historical salaries is something of a black art (a speciality of demons). Maxwell's salary would be the equivalent of around £39,000 in terms of the goods it could buy. However, it would be the equivalent of around £300,000 in proportion to the change in the earnings of an average worker between the two periods.

[‡] In practice King's could not award BA or MA degrees at the time, but on successful completion, a student became an AKC – an Associate of King's College.

[§] Just as dangerous as it sounds. Used at the time as the explosive charge of mines and torpedoes, and for blasting (and later as a rocket propellant), though oddly, given the name, not typically used in guns.

[¶] The ribbon is usually described as being tartan, but pedants point out that tartans usually have two colours, where the ribbon had three.

[||] Don't let scientists ever tell you that they don't sometimes benefit from luck. The photographic plates Maxwell used were not sensitive enough for the relatively low-energy red light to produce a good red image when the red filter was used. But, luckily, the red sections of the tartan were also good emitters of ultraviolet, which passed unhampered through the red filter and made the appropriate impact on the plate.

[**] In the absence of antigravity, which despite many YouTube videos and conspiracy theories to the contrary, is yet to be demonstrated. It was speculated at one time by serious physicists that the gravitational force between matter and antimatter could be repulsive rather than attractive, but there is as yet no evidence for this.

[††] Known as a magnetic monopole.

[‡‡] It should be stressed that, as with his fluid model, the spheres were just an analogy. There was no suggestion that space really was filled with spheres, though eventually the picture would resolve as something Maxwell felt was closer to reality.

[§§] Ever since Newton, some have liked to mock the idea of centrifugal force flinging things outwards as a body rotates, pointing out that the flung objects are simply following their natural trajectory in a straight line, and the 'real' force involved is usually a 'centripetal' force, towards the centre, countering the inclination to move outwards. However, this is just a distinction of the frame of reference used to examine the forces – it depends where you look at the effect from – and centrifugal force can still be a useful way to describe an effect.

[¶¶] Induction is how, for instance, mobile phones and electric toothbrushes can be charged contactlessly. A changing current in the base produces a changing magnetic field which induces a changing current in the device to charge the battery.

[||||] Maxwell called the tiny spheres 'idle wheels' and the hexagonal cells 'rotating vortices', a term based on his earlier fluid model. He would come to think of the cells as actual vortices in the ether.

[***] To really be true Victorian in look and feel, the model should have been constructed of brass and mahogany.

[†††] Many see this as ironic, as he would later make a discovery that made the ether unnecessary but refused to accept this implication.

[‡‡‡] Some current physicists suggest that modern equivalents of the ether might be dark matter or the inflationary concept in the Big Bang theory, which have become engrained

in our way of thinking but have limited evidence to support their existence.

§§§ *Philosophical Magazine* may sound like a lightweight periodical, a *Popular Science* of its day, but this venerable scientific publication began in 1798 and would carry papers from many of the Victorian big-hitters including Davy, Faraday, Maxwell and Joule. It is still in print. By comparison, the journal *Nature,* which would eventually eclipse it, first appeared in 1869. *Philosophical Magazine* began as a general journal of natural philosophy, but soon came to specialise in physics.

Demonic Interlude V

In which the demon becomes a star

With his model representing the inner working of electromagnetism established, my master was well down the road to featuring in the scientists' hall of fame. He wasn't quite there yet – no one could entirely love a model based on hexagonal vortices and ball bearings, not even a demon, but he had laid the foundation for his later glory.

It might seem that I'm biased and am singing my creator's praises more than is justified – especially as he's not exactly remembered by the public like a Darwin or an Einstein – but to quote Richard Feynman, generally accepted to be one of the twentieth century's greatest physicists:

> From a long view of the history of mankind – seen from, say, ten thousand years from now – there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics.

Feynman was a fan.

Victorian computer dating

It can be difficult to get a feel for the personality of a Victorian gentleman; so much that was written about individuals back then was stiff and lacked personal insights. It's not necessarily easy for you to imagine JCM as a real person (certainly compared with someone who knew him, like me). So, it's lucky that he filled in a questionnaire about himself – the sort of thing you might use when applying for a computer dating site these days – for fellow scientist Francis Galton.

Galton has had a bad press of late as an advocate of eugenics, but he did wide-ranging, useful work and was fascinated by the statistical analysis of people and their heredity, particularly when considering the nature of genius. In 1874, Galton published a book called *English Men of Science,*[*] based on around 200 questionnaires, which he had persuaded

Fellows of the Royal Society to fill in. It was Galton's book that gave us the first sighting of the idea of 'nature versus nurture' (using those terms) and his research is seen as the starting point of the use of questionnaires in psychology.

We, however, can ignore the rest and pick out JCM's replies to get a little more insight into Maxwell, the man. We are told that he was 5 feet 8 inches (1.73 metres) tall, and was 'often laid up'[†] before he was nineteen, but never since – what's more, he had never had a headache. When asked about his 'mental peculiarities', Maxwell wrote:

> Fond of mathematical instruments and delighted with the forms of regular figures and curves of all sorts.
>
> Strong mechanical power. Extremely small practical business. [He also noted that his father was a 'Very great mechanical talent'.]
>
> Strongly affected by music as a child, could not tell whether it was pleasant or painful, but rather the latter; never forgot melodies or the words belonging to them and these run through the mind at all times and not merely when the tunes are in fashion; can play on no instrument and never received instruction in music.
>
> Great continuity and steadiness; gratitude and resentment weak; στορχη[‡] pretty strong; not gregarious; thoughts occupied more with things than with persons, social affections limited in range; given to theological ideas and not reticent about them; constructiveness of imagination; foresight.

Another fascinating little insight into JCM's mind is from his answer to the question 'Origin of Taste for Science':

> I always regarded mathematics as the method of obtaining the best shapes and dimensions of things; and this meant not only the most useful and economical, but chiefly the most harmonious and the most beautiful.
>
> I was taken to see William Nicol [see page 24] and so, with the help of Brewster's Optics and a glazier's diamond, I worked at polarisation of light, cutting crystals, tempering glass, etc.
>
> I should naturally have become an advocate by profession, with scientific proclivities, but the existence of exclusively scientific men, and in particular of Professor Forbes, convinced my father and myself that a profession was not necessary to a useful life.

The demon's catechism

As my master was becoming more famous, I too was getting better established and being recognised by many physicists as an entertaining diversion – you might say I was becoming a star. So much so, that JCM felt obliged to write up a little biography of me in the form of a religious catechism[§] for his friend Peter Tait. Rather irritatingly, he used the plural ‘demons’, where anyone with any sense knows that I am a singular entity:

> *Concerning demons*
>
> 1. Who gave them this name? Thomson.
> 2. What were they by nature? Very small *but* lively beings (capable of obeying orders but) incapable of doing work[¶] but also able to open and shut valves which move without friction or inertia.
> 3. What was their chief end?[||] To show that the 2nd Law of Thermodynamics has only a statistical certainty.
> 4. Is the production of an equality of temperature their only occupation? No, for less intelligent demons[**] can produce a difference in pressure as well as temperature by merely allowing all particles going in one direction while stopping all those going the other way. This reduces the demon to a valve. As such value him. Call him no more a demon but a valve like that of the hydraulic ram,[††] suppose.

The apparent belittling here runs counter to the appreciation of William Thomson, who later remarked of me that I was an intelligent being who was different ‘from real living animals only in extreme smallness and agility’. Some have suggested that Thomson’s enthusiasm to portray me as non-mechanical was a conscious attempt to oppose the theory of the ‘X Club’, whose members, including the Irish physicist John Tyndall and English biologist Thomas Huxley, were strong supporters of the idea that living things were mechanical automata with no concept of a soul required.

Whether or not Thomson’s motivation was partly religious, as it happens, JCM was wrong in this instance – turning his simplified demon into a valve for the temperature and pressure experiment would not work (he didn’t need to get in extra staff, incidentally – this is something I would happily have helped him with).

Richard Feynman, a physicist with his own demons, described in his acclaimed ‘red book’ lectures on physics that any basic mechanical replacement for a demon would heat up as a result of its efforts – so much so that it would eventually be jittering around far too much to do its job. As well as preventing us demons from being put out of a job, Feynman was pointing towards something that is special about my role – it’s not possible to do the job without being able to deal with information. You’ll never find a non-intelligent, mechanical demon.

It ought to be stressed, though, that JCM was not setting out to wreck the second law of thermodynamics. He was entirely happy with its validity. But his development of the statistical approach to the kinetic theory of gases meant that he was aware that at its heart, the second theory was about probabilities, not certainty. As the English physicist James Jeans would later point out in a textbook:[‡‡]

> Maxwell's sorting demon[§§] could effect in a very short time what would probably take a very long time to come about if left to the play of chance. There would, however, be nothing contrary to natural laws in one case any more than the other.

A demon like my humble self was perfectly capable of taking things in a direction that was extremely unlikely but not impossible in normal circumstances.

So, let's get back to JCM as he takes a break from the city after getting together his latest thoughts on electromagnetism.

Notes

1 – Richard Feynman's citing the development of Maxwell's electromagnetic theory as the most significant event of the nineteenth century is from Richard Feynman, *The Feynman Lectures on Physics, Vol. II – the new millennium edition* (New York: Hachette, 2015), section 1–11.*

2 – Maxwell's answers to Francis Galton's psychological questionnaire were accessed on the Clerk Maxwell Foundation website, available at: www.clerkmaxwellfoundation.org/FrancisGaltonQuestionnaire2007_10_26.pdf

3 – Maxwell's mini-biography for the demon sent to Peter Tait is from Cargill Gilston Knott, *Life and Work of Peter Guthrie Tait* (Cambridge: Cambridge University Press, 1911), pp. 214–15.

4 William Thomson's remark that the demon was, in effect, living is from William Thomson, 'The Kinetic Theory of the Dissipation of Energy', *Nature*, 9 (1874): 441–3.

5 – Richard Feynman's demonstration that a mechanical valve could not do the work of a demon is in Richard Feynman, *The Feynman Lectures on Physics, Vol. II – the new millennium edition* (New York: Hachette, 2015) sections 46.1 to 46.9.

6 – The comment by James Jeans that the demon merely achieved what could happen over a longer timescale anyway is from James Jeans, *The Dynamical Theory of Gases* (Cambridge: Cambridge University Press, 1921), p. 183.

* The Feynman lectures don't have page numbers.

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[*] The word 'scientist' was probably still not widely accepted enough at this point for Galton to be comfortable with using it in his title. Women, of course, given Victorian sensibilities, did not come into it. It might seem odd that the entirely Scottish JCM should be listed as an 'English' man of science. Galton's main selection mechanism was those who lived or worked relatively near London, and at the time Maxwell was in Cambridge. It's also true that the word 'English' was often loosely used as an alternative to 'British' at the time.

[†] That’s to say unwell. JCM was what was known as a sickly child.

[‡] Greek for affection or love.

[§] A catechism is a summary of doctrine, often phrased as questions and answers. Maxwell attended Dean Ramsay’s catechism classes in Edinburgh as a teenager, thanks to his Aunt Jane.

[¶] There he goes again with the personal comments.

[||] It is not just the question and answer format that shows that this was based on a catechism – a well-known example, The Westminster Shorter Catechism of 1647, has for one of its questions: ‘What is the chief end of man?’

[**] Clearly this part does not refer to me as an individual. Some of my colleagues, certainly.

[††] This is a device that employs water pressure to raise part of a head of water higher than it originally was, using the greater pressure of the large body to move the smaller amount. It makes use of two one-way valves.

[‡‡] The author would like me to point out that he still finds it remarkable, bearing in mind that the textbook quoted above was written in 1904, that while at university, he had tea with James Jeans’ widow, the organist Lady Susi Jeans. She was, admittedly, significantly younger than her husband.

[§§] This makes me sound worryingly like a Royal Mail employee.

Chapter 5

Seeing the light

With his new model written up, Maxwell used the long summer vacation* of 1861 to head back to Glenlair with Katherine. Academics often take this time away to refresh themselves by either totally ignoring academic work or dealing with a pet project that had been sidelined, and it seems that it was Maxwell's intention to concentrate on the Glenlair estate, but he could not get his electromagnetic model out of his mind. There was something not quite right in his mechanical analogy, impressive though it was at predicting most electromagnetic effects. This might simply have been because he was stretching the analogy too far, but discovering whether or not this was the case was nagging at him like the throbbing of an aching tooth.

The power of flexible cells

In his model, the hexagonal cells and the small spheres transferred rotating motion to adjacent components, so the movement spread up the diagrams shown on previous pages. But in a real mechanical system this would usually result in a loss of energy. This might seem to be something to do with electrical resistance, but the picture didn't fit – and the resistance took place in the wire, not throughout the ether, which his model represented. However, there was a way to fix this if the rotating cells were no longer rigid, but he allowed them to give way under pressure, a property known in physics as being elastic.

It was probably easier to think constructively in the familiar and relaxed surroundings of Glenlair, away from the bustle of London, with Katherine proving an effective sounding board. Maxwell envisaged a circuit consisting of an insulator between metal plates. The pair of plates would be connected to a battery, so an electric field extended through the insulator. In his model, in an insulator the tiny spheres could not flow, as they were attached to the hexagonal cells. But if the cells were flexible, each cell could twist around a little on its axis. So, in effect, a small amount of current would flow from the plate on one side to the plate on the other due to the displacement of the cells, before the torsion in the elastic material became strong enough to resist any further motion.

At this point, one plate would be relatively positively charged, and one would be relatively negative. This meant that there would be an attraction between the plates. And, magically, the elastic mechanism he had suggested produced an attraction out of nowhere, because the twisting of the cells would make the ether contract. Each cell would shrink, just as a spring gets smaller as it is wound up, which would pull the plates towards each other. This pull provided the missing factor in his model, electrostatic attraction.

If the battery were now removed from the circuit, that tension in the cells would remain. The attractive force would still be there. But if the two plates were then connected by a wire, the current would briefly flow between them, releasing the twists from the flexible cells – there would be a discharge of electricity and the attraction would disappear. He was describing the action of an electrical component that used to be called a condenser and is now known as a capacitor.

Just as Maxwell had allowed the density of the cells in his model of the ether to be modified by materials it passed through to account for different magnetic properties, he was able to do the same for substances with different electrical properties. If the gap between the metal plates was filled with different materials – air or wood or mica, for example – the result would be a change in the elasticity of the ether's cells. A substance like mica (a naturally occurring silicate crystal that forms sheets and was often used as an insulator in early electrical experiments) is more susceptible to electrical charges than, say, air. Such a material, known as a dielectric, would, in his model, make the cells twist more easily, so that a bigger charge was held and more current would flow when the plates were connected.

By making those hexagonal cells elastic, able to twist and tighten, he had brought electrical attraction into his model. As an idea it worked, and by using the relatively new techniques that applied differential calculus – the mathematics of change – to vectors,[†] he was able to use his model to provide a mathematical description of electrical and magnetic fields.

Maxwell's new version of his model portrayed the ether as a kind of invisible energy store. Static electrical energy was potential energy, stored away in the ether like the energy in a spring, while magnetic energy was kinetic energy, like that of a rotating flywheel. And his model showed that the two types of energy were unfailingly linked. Making a change in the level of one influenced the other.

This was a remarkable achievement. But, of itself, building a model that matches reality does not necessarily make it useful. For many centuries, pre-Renaissance astronomers used a model of the structure of the universe based on epicycles, where a complex combination of circular movements allowed everything to rotate around the Earth, while explaining the oddities, for example, of the observed orbit of Mars, which reverses its direction in the sky. We now know that this is because the planets are orbiting the Sun, not the Earth. The epicycle model matched well to what was observed, but it did not give astronomers anything new to test it with – it was designed to match observation and the stubborn belief that the Earth was at the centre of the universe, and it did nothing more. But Maxwell's model went further. It predicted something that had not previously been observed.

Waves in the ether

If the ether were truly like Maxwell's model,[‡] there was an extra component to be added to his mathematics. Even empty space was filled with the ether, and this meant that you should always get that little twitch of movement in the tiny spheres from the twisted elastic cells. This extra 'displacement current' on top of the usual conduction current added a component to his equations that made them mathematically complete. In terms of the accuracy of his model in reflecting what was actually observed, this was the turning point. Yet the introduction of elasticity into the cells had another, just as important, implication.

If a material is elastic – if the substance that makes it up has some flexibility – it is possible to send a wave through it. Waves involve a repetitive displacement of the parts of the material the wave is passing through, and that can only happen if the material is not completely rigid. Imagine Maxwell's cells and spheres stretching through the void of space. If there were a twitch of movement in a row of spheres, caused by electrical energy, that would cause a brief torsion in the adjacent cells – representing a short movement of magnetic energy. That in turn would twitch the next row of spheres – generating a new electrical surge.

This succession of twitches would pass through the apparently empty space occupied by the ether. It would not progress instantaneously, as the cells would have some inertia, so each would take a little time to get moving. What Maxwell's model was predicting is that it should be possible to send out a wave of alternating electrical and magnetic displacement through an insulator – even through the vacuum of space – because the ether was always present. And as the displacement in the spheres and cells was happening at right angles to the direction this disruption was travelling, what was observed would be a transverse wave, like ripples on water, where the material is displaced at 90 degrees to the direction of travel of the wave.

The concept of the displacement current introduced a role for the theoretical physicist that seems to have been Maxwell's own invention. At the time, theoretical physicists did most of their work producing theories to match observations. But Maxwell saw a role for the theoretician in looking for the holes that were left in experimental evidence and making predictions that could later be tested. The displacement current was not the result of any observation – it was purely a prediction from his model. This apparently small contribution, often overlooked in popular descriptions of Maxwell's work, was revolutionary. There was considerable resistance to this approach from some of his colleagues, but Maxwell's daring step became a central role of theoreticians, to the extent that in some fields this kind of deduction from models came to dominate.

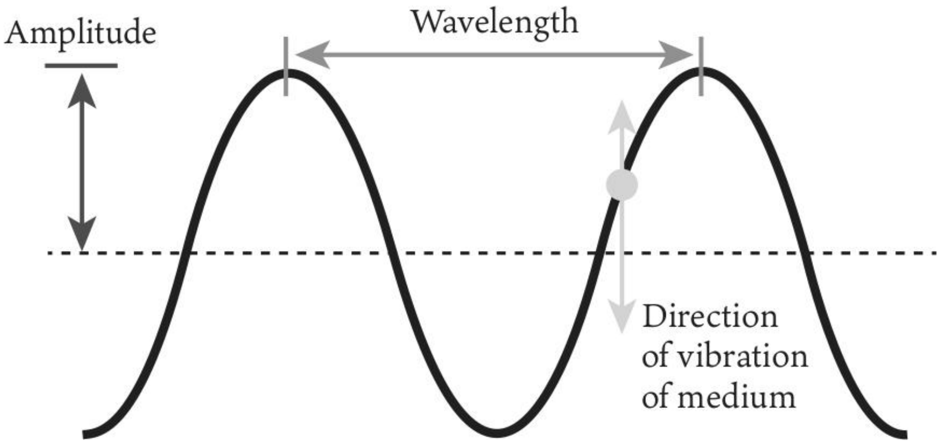

FIG. 5. *The features of a transverse wave.*

The introduction of the displacement current was a remarkable achievement for Maxwell's method – other contemporary attempts to explain electromagnetism relied still on action at a distance. Dismissing Faraday's electrical and magnetic fields, they used instead the idea of point charges producing a force at a distance and did not come up with this extra component which would allow for electromagnetic waves. Einstein considered this move to be crucial. Writing in his book *Autobiographical Notes,* he said:

> The most fascinating subject at the time I was a student was Maxwell's theory. What made this theory appear revolutionary was the transition from action at a distance to fields as the fundamental variables … it was like a revelation …

As it happens, there already was a transverse wave known to science that travelled through insulators and even empty space – light. What's more, as we have seen, Maxwell's hero Faraday had speculated that light somehow involved electricity and magnetism.

Remember that in 1846, when Maxwell was fifteen, Faraday had filled in for Charles Wheatstone at a lecture and had told his audience:

> The views which I am so bold as to put forth consider, there-fore, radiation as a high species of vibration in the lines of force which are known to connect particles, and also masses of matter, together. It endeavours to dismiss the aether, but not the vibrations.

In his inspired vision, Faraday was prepared to go a step further than Maxwell. Where Maxwell believed that his model of cells and spheres represented the ether, Faraday believed that the fields of electricity and magnetism extended through empty space without the need for an ether.

Either way, both had realised that light was a vibration in those fields, Faraday in visionary concept and Maxwell with the mathematical backing of his mechanical model.

Seeing the light

We don't know the exact process by which Maxwell realised that the waves his model predicted seemed remarkably similar to light, but it's hard to imagine that he was unaware of Faraday's 'Thoughts on Ray-vibrations' talk. Whatever the means of reaching this idea, Maxwell's model gave him a way to test out whether this relationship between light and electromagnetism was valid. It was known that the speed of waves through a medium could be calculated from a combination of the elasticity of the medium and its density. In his model, elasticity corresponded to the electrostatic force and density to the magnetic equivalent.

Although not all the values required were perfectly pinned down for his model, if Maxwell took the minimum values for the elasticity of a vacuum, the speed of the predicted wave would match the velocity produced by dividing the unit of magnetic charge by the unit of electrical charge, which was unlikely to be a coincidence. Maxwell was able to calculate that his model predicted that in a vacuum, such electromagnetic waves should travel at 193,088 miles per second (310,700 kilometres per second).

All Maxwell had to do was to compare his prediction with the speed of light, a value that had first been made calculable in 1676 by the observations of Danish astronomer Ole Rømer of variations in the timings of the moons of Jupiter as the distance between the giant planet and Earth varied. More recently it had been measured by French physicist Armand Fizeau using a mechanical device which sent flashes of light from a fast-rotating toothed wheel down a 9-kilometre track, before returning the light through the wheel, using the speed of rotation of the wheel to measure the elapsed time.

Unfortunately, Maxwell did not have any documentation on Fizeau's work with him at Glenlair,[§] and though his speed for electromagnetic waves was certainly relatively close to what had been measured, he couldn't remember the value sufficiently well to be sure how effective his prediction was. He had to wait until his return to London in October to compare his theoretical wave's speed with that of light. Back at King's College he discovered that the latest figure from Fizeau gave light speed as 195,647 miles (314,850 kilometres) per second, with other estimates in the 192,000 to 193,118 miles per second (308,990 to 310,790 kilometres per second) range. This was less than 1.5 per cent different from his calculated speed.

Such a similarity seemed highly unlikely to be a coincidence. Maxwell wrote:

> The velocity … agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau, that we can scarcely avoid the inference *that light consists ... [of] undulations of the same medium which is the cause of electric and magnetic phenomena.*¶

His 'mechanical analogy', which had aroused in Poincaré that 'feeling of discomfort and even of mistrust', had revealed the truth behind a mystery that had puzzled humanity for millennia – what was light?

Although Maxwell had considered *On Physical Lines of Force* to be complete with the first two parts, he now decided to extend it to add a third section in 1862 which included the displacement current and electromagnetic waves. This was soon followed by a part four, as he realised that his electromagnetic waves would account for another previously unexplained phenomenon.

We have already seen on page 25 how Maxwell as an undergraduate had made use of polarised light in his home laboratory. Faraday had also studied polarised light and had discovered that passing such light through a magnetic field would rotate its direction of polarisation. Now that Maxwell had identified light as a combination of electrical and magnetic waves at right angles to each other, and assuming that polarisation represented the direction of these waves, it was natural that a magnetic field would have an influence on the changing fields in the wave and cause them to rotate, just as it caused a wire carrying a changing current to rotate in an electric motor.

Too heavy for one person to discharge

Maxwell had a little more time available for his own work after his return to London in October 1861 with the appointment of George Robarts

Smalley as a physics lecturer to assist him. Maxwell had complained to the college that his teaching requirements were ‘too heavy for one person to discharge’. This appointment did not represent any financial generosity on the part of King’s College. Smalley’s pay of 7 shillings per student per term was deducted from Maxwell’s salary.

Smalley continued in the post until July 1863, when he was appointed Astronomer Royal for New South Wales. Maxwell wrote a reference for Smalley to the British Astronomer Royal, George Biddell Airy, noting that:

> I believe Mr Smalley to possess the scientific knowledge and the habits of accuracy which would fit him for work at the Observatory … I consider that he would be steady, accurate and skilful in Observatory work.

William Grylls Adams replaced Smalley (and later took over Maxwell’s own position). Smalley and Adams took some of the weight from Maxwell’s shoulders.

Despite this reduction in work pressure while in London, Maxwell remained at his happiest when back at Glenlair. Here he could both think in peace about his physics and enjoy the rural life. In a letter written from Glenlair just after Christmas 1861 to Henry Droop, who had become a friend while they were both fellows at Trinity College, Cambridge, Maxwell noted:

> I have nothing to do in King’s College till Jany. 20, so we came here to rusticate. We have clear hard frost without snow, and all the people are having curling matches on the ice, so that all day you hear the curling-stones on the lochs in every direction for miles, for the large expanse of ice vibrating in a regular manner makes a noise which, though not particularly loud on the spot, is very little diminished by distance.

It shouldn’t be deduced, though, from his pleasure at having free time, that Maxwell was the kind of scientist whose only concerns were his own research and who had little interest in his students (as was the case with, say, Newton or Einstein). As we have seen, he stood up for his students in the use of the library and he lectured to working men. A good example of his attention to detail in this respect was a letter he wrote to J.W. Cunningham, the secretary of King’s College London, in December 1862.

> Dear Sir
> I am very anxious that the examination papers in Mechanics should be printed from type instead of from stone.

> I find that the lithographic papers are printed so that even if everything is plain in perfect copies, uncertainties exist in other copies which are very apt to make the examination not quite a fair one.
>
> Mr Smalley has the M.S. and expects to give it in at the office today.

Lithography, literally stone writing, is a printing technique where the dark parts of an image (the letters in a text) are marked out on the surface of a flat piece of stone – typically limestone – (or later metal) with a resistant substance such as wax or fat. Then the surface is treated with acid, which etches into the surface where there is no resistant material. The surface is cleaned then moistened, with water being retained in the etched sections between the letters or raised imagery. Finally, an ink that is immiscible with water is applied – the ink stays on the nonetched parts, and so reproduces the image or text.

Related, but more sophisticated techniques known as offset lithography and photolithography are still in use today, for printing and for producing printed circuits respectively (though, despite the names, no stone is involved). However, in Maxwell's time the process, though relatively cheap, was not as consistent in its results as using moveable type – metal letters fixed into a frame. Maxwell, as always a champion of the students, was ensuring his examination papers were legible despite additional cost to the college.

The Great London Exposition

Maxwell also continued with his interest in communication of science to the wider public that had come through in both his work with the British Association and in lecturing at the Royal Institution. An opportunity arose in 1862, when it was decided to follow up on the huge success of the 1851 Great Exhibition. Although France had put on a pair of national events earlier, the Great Exhibition was effectively the first World's Fair, a chance to show off and revel in the wonders of Victorian technology.

Such was the success of the first event that its profits funded the construction of the Science Museum, Natural History Museum and Victoria and Albert Museum. Before they were built, however, the land that would be the site of the Natural History Museum was used to house the Great London Exposition of 1862, also known as the International Exhibition.

As a money-making event, this proved a relative failure compared with its predecessor, doing little more than break even thanks to the far more lavish building constructed for the purpose, but still around 6 million people filed through the vast halls. Maxwell was responsible for producing the guide to a section of philosophical (scientific) instruments connected with light. His might have been a small contribution to a massive venture, but he went far beyond a simple catalogue, taking the opportunity to throw in some history of science and descriptions of the physical mechanisms involved, showing his expertise with leading-edge experimental optics.

Meanwhile, once Smalley was in place at King's, there was soon an opportunity for Maxwell to make use of that freed-up time. It wouldn't be understating things to say that Maxwell's model of electromagnetism and its prediction of electromagnetic waves was a huge breakthrough – not only in this specific case, but also for the way that physics itself would be undertaken, in which Maxwell's approach of producing a model and testing its predictions has become a central part of the scientific method.[||] Even so, and despite a largely positive reaction when he wrote it up, Maxwell was not entirely happy. Perhaps Poincaré's mistrust stung him – but he felt it ought to be possible to take away the framework of analogy, removing his mechanical model and keeping only the pure, untrammelled mathematics.

Notes

1 – Albert Einstein's observation that the most fascinating subject as a student was Maxwell's theory is quoted in Albert Einstein, *Autobiographical Notes* (Illinois: Open Court, 1996), pp. 31–3.

2 – Maxwell's words on the inference that light was an electromagnetic wave are from his paper 'On Physical Lines of Force' in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 1 (Cambridge: Cambridge University Press, 1990), pp. 499–500.

3 – Maxwell's comment about his teaching duties being too heavy is from King's College London Archives, King's College Council, Vol. I, minute 42, 11 October 1861.

4 – Maxwell's reference for Smalley's application as Astronomer Royal for New South Wales is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 87.

5 – Maxwell's letter mentioning the noise of curling to Henry Droop, written from Glenlair on 28 December 1861, is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 703.

6 – Maxwell's letter to J.W. Cunningham on printing the examination papers in mechanics is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 61.

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* Long by most people's standards. After the six-month summer vacation at Aberdeen, the mere four months allowed by King's College may have seemed quite short to Maxwell.

† A vector is a quantity with both size and direction, where a scalar quantity only has size. Speed is a scalar – 50 kilometres per hour, for example. Velocity is a vector – 50 kilometres per hour heading north, for example.

‡ Always bear in mind that the ether does not exist. This was Maxwell's thinking at a time when it was still assumed that there was such a thing.

§ Ironic, given that Maxwell's work would provide an essential foundation for the internet that enables anyone to look up this value pretty much instantly.

¶ Maxwell's italics.

|| In fact there was a third reason this breakthrough was so important, though Maxwell would not live to witness it. Maxwell's model required light to always travel at a particular speed in a vacuum, a fact that Einstein would use to develop his special theory of relativity.

Chapter 6

Science by numbers

Like many Victorian scientists, Maxwell did not suffer from the modern tendency to remain constrained by a tight focus – he clearly appreciated the chance to roam free across the topics covered by physics. This is apparent in some of his letters, where he happily discussed a wide range of physical subjects with fellow scientists.

A good example would be a letter that Maxwell wrote in August 1863 to George Phillips Bond, an American astronomer based at Harvard University. Bond had met Maxwell in London that May and subsequently had written to him both about the rings of Saturn and about comets. At the time, the behaviour of comets' tails was a puzzle. Back in 1619, the German astronomer Johannes Kepler had pointed out that the tails of comets always pointed away from the Sun. When the comet is heading into the solar system, towards the Sun, its tail flows out behind it, but when the comet is moving in the opposite direction away from the Sun, the tail lies confusingly in front of it.

This behaviour suggested to Kepler that, rather than being left behind like a stream of smoke from a moving flame, the comet's tail was being pushed by something emanating from the Sun. Somehow, the Sun's rays were forcing the comet's tail away. Late in his career, Maxwell would come up with a better explanation for this (see Chapter 9), but in responding to Bond, he speculated about the nature of the ether that he still believed was the medium for light waves.

Maxwell wrote of that medium:

> [I]t is well able to do all that is required of it, whether we give it nothing to do but to transmit light and heat or whether we make it the machinery of magnetism and electricity also and at last assign gravitation itself to its power.

Given Maxwell's discovery of the nature of light, it's no surprise that he wanted to bring electricity and magnetism into the mix, but the idea of gravitation also being involved may seem a little odd. However, it fitted well with ideas that had been circulating ever since Newton's day.

Newton famously claimed not to have a hypothesis for *how* gravity worked at a distance, writing in his masterpiece, the *Principia,* 'hypotheses non fingo', usually translated as 'I frame no hypotheses'.[*] This wasn't true. As a great supporter of particle-based theories – thinking, for example, that light was a collection of particles or 'corpuscles' – Newton did have a particle-based theory of the mechanism of gravity, variants of which would be developed up to the time that Einstein put gravity on a sound mathematical footing in 1915.

As we have seen, the idea based on invisible particles flowing through space and pushing on massive bodies was simple and attractive,[†] but it had one major flaw, which various scientists over the years would attempt to overcome with what were ultimately fudges. In its simple form, the theory predicts that the gravitational force will be linked to the size of the attracting body. While size is usually a factor, it's only because big things tend to be more massive. Newton had shown it was the mass of the bodies involved that determined their gravitational attraction, not their size. Explanations of gravitation based on the particle pressure theory had to be modified to account for this.

What Maxwell seems to have had in mind in his letter to Bond was a similar mechanism for gravity, but one that depended on pressure in the ether. As he put it:

> If we could understand how the presence of a dense body could produce a linear pressure radiating out in straight lines from the body and keep up this kind of pressure continually, then gravitation would be explained on mechanical principles and the attraction of two bodies would be the consequence of the repulsive action of the lines of pressure in the medium.

He drew an image showing the Sun emitting lines which then hit a body and curve around it in parabolic shapes, and went on to speculate that the comet's tail is a result of these pressure lines, pushing away from the Sun. But he couldn't explain why the lines of force would be visible as a tail (we now know the tail is gas and dust, vaporised from the comet), asking:

> Is there anything about a comet to render its lines of force visible? and not those of a planet which are much stronger? I think that visible lines of gravitating force are extremely improbable, but I never saw anything so like them as some tails of comets.

Maxwell's ideas here may not have been fruitful, but they demonstrate the breadth of his thinking.

The viscosity engine

Rather than immediately refining his model for electromagnetism after its initial triumph, Maxwell returned to his old sparring partner, the nature of a gas, looking specifically at a property of fluids known as viscosity – a measure of the liquid's (or gas's) resistance to shearing forces – effectively how thick and gloppy the material is.

At the time, it was thought that the viscosity of a gas varied as the square root of the temperature – if the temperature quadrupled, for example, the viscosity would double. This would not be the temperature as we measure it for domestic use, from the arbitrary starting point of the freezing point of water, but from the coldest possible temperature, absolute zero, which is around –273.15°C (–459.67°F). The concept of absolute zero had been around since the eighteenth century, but Maxwell would have had an appropriate scale to use thanks to his friend William Thomson, who in 1848 devised the Kelvin scale (Thomson was later ennobled as Lord Kelvin), starting at absolute zero.

However, Maxwell, who always seemed to enjoy bridging the gap between experiment and theory, undertook a series of experiments to confirm or deny the behaviour of viscosity with temperature. His schedule at King's College left him plenty of time for experimental work, but unlike a modern physics professor he did not have access to a laboratory at the university and had to perform his experiments in the attic of his house.

Maxwell's main experimental device for investigating the viscosity of gases consisted of a series of discs along a vertical wire spindle, alternating fixed discs and discs which rotated together by twisting the wire. The discs were contained inside a glass chamber which meant that Maxwell could alter the pressure with an air pump, or change the contents to a different gas to discover the impact on the viscosity. This was no table-top apparatus – it stood above Maxwell's height on the attic floor (see Figure 6). The discs were 10.56 inches in diameter and the wire was four feet long. Maxwell started the discs moving using magnets outside the case, sliding them from side to side until the discs were twisting back and forth on the wire. The resultant oscillation was slow – Maxwell notes that ‘the period of a complete oscillation was 72 seconds and the maximum velocity of the edge of the disks was about 1/12 inch per second’.

When the discs were oscillating, the resistance of the air between the turning discs and the nearby fixed discs (having fixed discs also minimised the impact of draughts) caused a dragging effect that enabled Maxwell to estimate the viscosity of the gas. Despite a dangerous-sounding setback – his glass chamber imploded when he reduced the pressure too much and it took him a month to get the apparatus working again – he soon had solid results, which he presented to the Royal Society in November 1865.

Because the whole point of the experiment was to see how viscosity varied with temperature, Maxwell and Katherine had to make extreme efforts to vary the temperature in the London attic. The near-contemporary biography of Campbell and Garnett notes that:

> For some days a large fire was kept up in the room, though it was in the midst of very hot weather. Kettles were kept on the fire and large quantities of steam allowed to flow into the room. Mrs Maxwell acted as stoker, which was very exhausting work when maintained for several consecutive hours. After this the room was kept cool, for subsequent experiments, by the employment of a considerable amount of ice.

Fig. 1

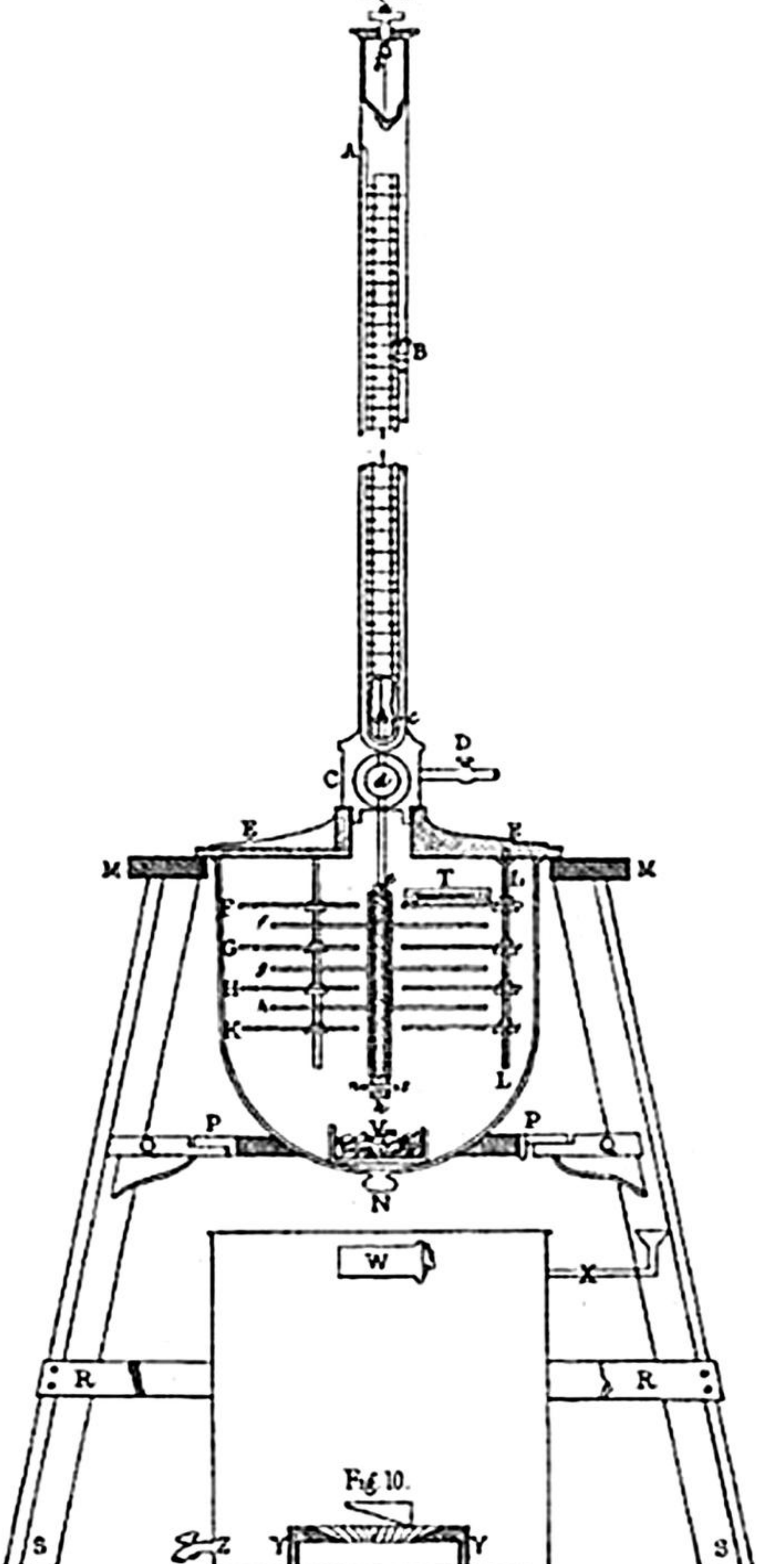

FIG. 6. *Maxwell's viscosity apparatus with the discs enclosed in the glass container like an inverted bell jar.*

The findings from this experiment proved a challenge to Maxwell's own theory of gases. It did confirm his surprise discovery that viscosity was independent of pressure. But his theoretical work had fitted with the previously assumed square root relationship between temperature and viscosity, while the experiments clearly showed that the viscosity actually was directly proportional to the temperature. You would only have to double the temperature to double the viscosity. Despite this, Maxwell's results did plenty for his reputation as an experimental physicist pushing the boundaries of knowledge. For the moment, though, he would be distracted from taking the work any further.

Stereoscopes and coffins

It's no great surprise that the distraction came from his old favourite topics of light and colour vision, but in his London home Maxwell turned this into a mix of research and parlour entertainment. In Victorian homes like Maxwell's it was not uncommon for visitors to be presented with a diversion that consisted of a new piece of technology. In the 1860s, many a parlour would be considered incomplete without a stereoscope, as essential a piece of middle-class home technology as a computer today.

A form of stereoscope – which combined two pictures portrayed as if seen from the positions of the two eyes to produce a 3D image – had been invented in the 1830s by another King's College professor, Charles Wheatstone.[‡] Maxwell was certainly aware of this as early as 1849, while at Edinburgh University, as he wrote to Lewis Campbell about 'Wheatstone's Stereoscope' and how Sir David Brewster had 'exhibited at the Scottish Society of Arts Calotype[§] pictures of the statue of Ariadne and the beast seen from two stations', which Maxwell comments 'when viewed properly, appeared very solid'. By the 1860s the combination of readily available stereoscopic photographs and a far less complex optical device to view them meant that stereoscopes were all the rage.

Maxwell himself later devised a significant improvement on the standard stereoscope, though it never took off commercially as it was both larger and more expensive than the traditional form. The parlour stereoscope consisted of a frame holding a pair of photographs (or drawn images) and a pair of lenses through which the viewer looked. This was essentially the same approach as used in the View-Master toy, popular from the 1940s and reaching a zenith in the 1960s, although this had seven pairs of images on a disc, rotated by pulling a trigger on the side of the viewer. The result of looking through the stereoscope was that the images were combined in the viewer's brain, producing a virtual 3D image.

The stereoscope was effective, but limited. Some people had trouble viewing the images, the experience was individual – only one person could look through the lenses at a time – and the virtual image was quite distant from the viewer. In 1867, Maxwell developed a 'real image' stereoscope, which used the standard pair of photographs and dual lenses, but then had another, single large lens in front. The viewer (or viewers, if they were close enough together) looked at this lens from a distance of a couple of feet and saw the 3D image floating in space just behind the large lens. Maxwell had a device assembled by the instrument makers Elliott Brothers, and gave a paper on it to the British Association in September 1887. He would later use it to demonstrate 3D images of curved surfaces and mathematical knots. Topology and knot theory were recreational activities for Maxwell for a number of years, over and above their bearing on his more mainstream work.

However, in the Maxwells' home, visitors could expect a more unusual experience. They would be taken up to the attic to have an encounter with 'the coffin'. This was Maxwell's latest light box for mixing red, green and blue light to produce a whole spectrum of possible colours, one at a time. The eight-foot-long box had caused some confusion to Maxwell's neighbours when it was delivered as it did resemble a straight coffin. For the visitor this would be simply a new and exciting experience, but for Maxwell it was an opportunity to collect data on the way a range of individuals – both normal sighted and colour blind – perceived different colours. For several years, around 200 visitors a year were subjected to the coffin in the attic.

A standard for resistance

A less entertaining but more practical diversion came over the matter of electrical units – the units used to measure, for example, electrical current or resistance – which were becoming increasingly important as electrical engineering and particularly telegraphy took off. It's hard to appreciate now what a fundamental breakthrough telegraphy provided in speed of communication. Two of Maxwell's friends, William Thomson and Henry Fleeming Jenkin, were involved in the biggest telegraphy project of the day, the transatlantic cable, and there was considerable concern that resistance in the cable would render the project unusable. Thomson, working with Faraday, had shown that if the resistance of the cable were too high, it could take as long as four seconds to send a single character.

With such a major technology at the mercy of a topic that had not been precisely studied, getting a better measure of resistance had far more practical application than just establishing a common unit. The British Association for the Advancement of Science saw Maxwell, with his expertise in electromagnetism, as the ideal person to be involved. The BA had set up a committee to study the requirements for standard units at the Manchester meeting in 1861 and Maxwell would play a major role in putting together the report to the Newcastle meeting in 1863.

Historically, units had been derived locally and this caused considerable confusion in international communication. Each country had its own definitions of units such as length or weight, which made it difficult to be sure what a measurement really indicated. This was nothing new. In his book *The Sand Reckoner,* the Ancient Greek mathematician and engineer Archimedes gave a size for the universe using the measure of 'stades' – multiples of the length of the running track at a stadium. A stadion (plural stades) was supposed to be 600 feet, but each city had its own definition of a foot. This means we can't know for sure what Archimedes intended, with a stadion being anything between about 150 and 200 metres. The BA felt that with electrical science becoming inherently international due to the undersea cables, this kind of uncertainty could not be allowed to happen again.

The new capabilities of electricity and magnetism required appropriate units and Maxwell therefore agreed to take on electrical standards with the help of the Edinburgh engineer Henry Fleeming Jenkin (among other things, the inventor of the cable car) and Balfour Stewart, a physicist who had worked with Forbes at Edinburgh and was director of the Kew Observatory in Richmond upon Thames. The small team produced a more rational system for defining units for resistance, current and the like, based on experiments they undertook at King's College.

This was an unusual piece of work for Maxwell in that it is pretty well the only significant true teamwork he did, rather than acting alone (with the exception of assistance from Katherine). It's not that he worked in hermetic isolation – letters between Maxwell and the likes of William Thomson and Peter Tait are full of scientific ideas and queries, where the physicists would use each other as sounding boards. But unlike modern science, there was very little true collaboration involved.

Many of the traditional units were relatively simple to pin down (if only a universal standard could be agreed on). These had started with a physical measure from nature, then been locally standardised by having a definitive example. The older measures of distance, for example, such as the foot and the mile, were dependent on typical human characteristics – the size of a part of the anatomy and one thousand paces (*mille passus*) respectively. The metre was slightly more scientifically determined, originally 1/10,000,000th of the distance from the North Pole to the equator on the meridian that ran through Paris. Each had become standardised to be represented by an official measure, though, as we have seen, these varied from country to country.

It was less obvious where a standard for voltage or current or electrical resistance would come from. Indirect measures were proposed that made use of equipment that translated one of the electrical measures into more familiar physical units. So, for instance, as it was known that the force between two electrical charges dropped off with the inverse square of the distance between them, it was possible to define a unit of charge (later called the coulomb) with a combination of force generated and distance between charged objects. This could then be used to calculate current (later the amp), which was a rate of flow of charge and so on.

Alternatively, current itself could be used as the way in. As the values involved in electromagnetic interaction became better known (though what was causing it was yet to be fully understood), force and distance could also be used as a measure of current between two interacting electrical coils. And a third option made resistance the starting point.

This involved measuring the deflection of a rotating coil under the influence of magnetism.

Because of the importance of understanding the properties of the transatlantic cable, resistance was a key focus for Maxwell's group at King's College, which would make real an elegant mechanism devised by William Thomson based on this third option. Thomson's design involved spinning a coil of wire in the magnetic field of the Earth and using the induced electromagnetism to counter the Earth's pull on a small permanent magnet. Because the size of the magnetic field of the Earth cancels out between the two effects, the amount that the permanent magnet is deflected away from magnetic north depends only on the size of the coil, the speed of its rotation and its resistance – so, given the first two values, the equipment can be used to calculate an absolute value for resistance.

The velocity of a resistor

The unit of electrical resistance, measured using Thomson's method, turned out to be velocity. This was not connected to the actual velocity of a signal through the wire (something that confused many of those working on telegraphy at the time). It was simply the consequence of taking the units of the different values such as distance and speed of rotation that went into the measurement – the resultant dimensions of the resistance were distance and time in the form of a velocity. The standard unit settled on was 10 million metres per second, which would soon after be called a B.A. unit, also known as an 'ohmad',[¶] which rapidly got shortened to ohm.[‖] At least, 10 million metres per second was the intended value, although a measuring error (surely not one of Maxwell's infamous arithmetic slip-ups) meant that the standard ohm was actually slightly larger than it should have been.

The Thomson design was not a trivial piece of apparatus to use effectively. The coil had to be rotated at a constant speed, with a considerable amount of effort put into the design by Jenkin to provide a governor to keep the rotation steady. The mechanism was constantly breaking down, and to make matters worse, it was sufficiently sensitive that when an iron ship passed on the nearby Thames, the detection magnet would be slightly deflected.[**] It took many months of admittedly sporadic work to get a satisfactory set of readings. After the initial report at the 1863 BA meeting, a further twelve months would pass before they were sure that the values were reliable.

Apart from the theoretical definition defined from the spinning coil, the King's team put together a 'B.A. standard resistor' design. This was a rather magnificent construction, first completed in 1865, consisting of a coil of platinum/silver alloy wire covered in silk for insulation and then wrapped around a hollow brass core. The whole thing was then coated in paraffin wax, with thick copper wires to link it to the circuit. To ensure a constant temperature, the resistor was suspended in a water bath. While a standard resistor could not be just put alongside another resistor for comparison by eye, as was the case with a standard distance rule, a simple piece of equipment known as a Wheatstone bridge made it possible to use the standard resistor to calibrate others.

What was particularly impressive was the forward-looking nature of the British Association committee involved in devising these units. At a time when most scientific work was mired in the clumsy Imperial units, the electrical units were based on the metric system. This meant that when the other scientific units were switched over to metric, there was no need to redefine the electrical standards. For example, an amp (electrical current) times a volt (electrical potential) was the unit of electrical power. At the time, mechanical power would have been measured in horsepower or foot pounds per minute. But when the metric system was fully adopted internationally in 1921, the unit of mechanical power was a watt – exactly equal to an amp times a volt.

Electromagnetism without visible support

It's possible that this refocusing on the practical side of electromagnetism was what pushed Maxwell to think again about his remarkable achievement in modelling the phenomenon. Although his mechanically-based model was remarkably effective, he understood why others found that it depended too strongly on analogy and he wanted to strengthen the theory's mathematical standing by a kind of scientific magic trick of removing the mechanical foundation and leaving the mathematics holding itself up by its own bootstraps.

Perhaps surprisingly, Maxwell focused on electricity and magnetism, rather than digging deeper into his theoretical basis for light as an electromagnetic wave. Although colour and vision would remain an interest throughout his life, he intentionally limited his theoretical developments on how light worked, perhaps because he felt that he was far closer to providing greater insights into the fundamentals of electricity and magnetism. He would never apply his theoretical approach fully to familiar behaviours of light, avoiding the whole business of how light and matter interacted[††] other than making a few initial notes on reflection and refraction, based on some work by the French physicist Jules Jamin. He commented, for example, ‘In my book I did not attempt to discuss reflexion at all. I found that the propagation of light in a magnetised medium was a hard enough subject.’

The move from mechanical model to a purely mathematical one was a remarkably original approach – arguably Maxwell’s greatest work of genius – and would provide the basis for modelling taken by the majority of physics theory right up to the present day. In a Royal Institution debate in 2004, four proponents put forward different names for individuals who could arguably be called the first scientist. I was one of these debaters, championing the thirteenth-century friar Roger Bacon. But another held out Maxwell to be the first. One of his arguments was facile – that the term ‘scientist’ was not brought into use until 1834, so no one working earlier could be one. But his other argument was that Maxwell was the first scientist in the modern sense because he moved from trying to establish the ‘true nature’ of physical reality to mathematically modelling it.[‡‡]

It is interesting to speculate whether Maxwell was influenced philosophically in this move by the work of the German philosopher Immanuel Kant. Certainly, Maxwell would have heard about Kant’s work in his university philosophy classes. Kant distinguished the phenomenal world – what we can experience – from the noumenal world – the actual underlying reality, which he called in German *das Ding an sich* (the thing itself). Kant suggested there was no point trying to know the reality – we could at best work with our interpretations of phenomena. Where most of Maxwell’s contemporaries still believed they could discover the truth that lay beneath, Maxwell’s approach of moving to a purely mathematical model seemed to reflect Kant’s dismissal of such attempts.

Nearly 100 years earlier, the Italian-born French mathematician Joseph-Louis Lagrange had taken the traditional mechanics based on Newton's work and transformed it mathematically into what is now called Lagrangian mechanics. This centres on a mathematical function called the Lagrangian, which pulls together all the information about the movements of the bodies in a system into a single structure. In mathematics, a function is a compact way of referring to one or more equations which take one set of values and change them into something else. It's like a mathematical sausage machine.

A very simple function might be one that takes a number and does something to it, for example, producing the square of that number. It would usually be written as f(x) – pronounced 'f of x' – and we could say in this case, for example, that f(5)=25. Mathematical functions proved a very powerful mechanism both in physics and later in computing, where functions are commonly used to provide operational modules which can perform the same operations on differing inputs inside a computer program. The Lagrangian consists of a set of equations based on differential calculus that link the velocity, momentum and kinetic energy of a body.

Although the route to developing the Lagrangian involved thinking about actual physical processes, once the function is established and found to match what is observed it can be considered totally detached from any analogy. Rather than relying on a mechanical model, this kind of function is a purely mathematical model. It is a black box where the user provides certain inputs, 'turns the handle' and gets the outputs. If what comes out matches observation, the function can be used without any idea of how the system it is modelling actually works.

In the mathematical belfry

Maxwell, the regular churchgoer, felt that the ideal analogy for a Lagrangian approach (he might have dismissed mechanical models, but he still loved using them to explain things) was a belfry. It's quite a lengthy quote, but it's worth taking it slowly and absorbing it because with this simple illustration, Maxwell is showing how he brought modern physics into being.

> We may regard this investigation as a mathematical illustration of the scientific principle that in the study of any complex object, we must fix our attention on those elements of it which we are able to observe and to cause to vary, and ignore those which we can neither observe nor cause to vary.[§§]
>
> In an ordinary belfry, each bell has one rope which comes down through a hole in the floor[¶¶] to the bell ringers' room. But suppose that each rope, instead of acting on one bell, contributes to the motion of many pieces of machinery, and that the motion of each piece is determined not by the motion of one rope alone, but by that of several, and suppose, further, that all this machinery is silent and utterly unknown to the men on the ropes, who can only see as far as the holes in the floor above them.
>
> Supposing all this, what is the scientific duty of the men below? They have full command of the ropes, but of nothing else. They can give each rope any position and any velocity, and they can estimate its momentum by stopping all the ropes at once, and feeling what sort of tug each rope gives. If they take the trouble to ascertain how much work they have to do in order to drag the ropes down to a given set of positions, and to express this in terms of these positions, they have found the potential energy of the system in terms of the known co-ordinates. If they then find the tug on any one rope arising from a velocity equal to unity[‖‖] communicated to itself or to any other rope, they can express the kinetic energy in terms of the co-ordinates and velocities.
>
> These data are sufficient to determine the motion of every one of the ropes when it and all the others are acted on by any given forces. This is all that the men at the ropes can ever know. If the machinery above has more degrees of freedom[***] than there are ropes, the co-ordinates which express these degrees of freedom must be ignored. There is no help for it.

Because Maxwell's earlier model was mechanical, it ought to be capable of being represented in a Lagrangian form, which would enable Maxwell to then ditch the cells and spheres, leaving them above the ceiling of the virtual bell ringers' chamber and simply dealing with the mathematical formulae that were the equivalent of the bell ropes. This was anything but a trivial task. He needed to stretch the mathematics of the time to enable it to cope with the added complexities of modelling electromagnetism. His work crucially depended on the ability to think of energy – potential and kinetic in the mathematical model – and on keeping the concepts of energy while moving to the different frame of electromagnetism.

It didn't help that many of the quantities to be dealt with were vectors – as we have seen (page 69), Thomson had previously introduced Maxwell to using vector mathematics in the earlier fluid model, but dealing with a mix of quantities in the Lagrangian framework, some vectors with size and direction, such as the strengths of the fields, others, such as electrical charge, scalars with just size, made the mathematics significantly more challenging.

Nevertheless, Maxwell achieved his goal, and by December 1864 he was able to present to the Royal Society his groundbreaking new mathematical model of electromagnetism, which he wrote up the next year in the seven-part *A Dynamical Theory of the Electromagnetic Field.*

A new physics

Generally speaking, there are two possible reactions to a truly novel theory. Either everyone is bowled over by its clarity – or they are baffled by the novelty. Maxwell's theory was very much of the second kind.[†††] His audience at the Royal Society were appreciative, but simply could not grasp what he was suggesting. Up to this point, physics had largely been a discipline that was about experiment and philosophical theory, with the minimum of mathematics that was required to do the job. Now that maths was taking the lead, many in the audience were simply incapable of keeping up.

The difficulty of grasping the theory was not just a matter of making it accessible to the general public. The audience at the Royal Society included many of the leading physicists of the day. William Thomson, for example, admitted that he never came close to understanding Maxwell's theory. His was the last generation of physicists who could become leading figures without a strong grasp of high-level mathematics.

The reaction, and also the difficulty of explaining a strongly mathematical piece of physics to the general public, was beautifully assessed by Michael Faraday a few years earlier in 1857 in a letter to Maxwell. Faraday wrote:

> There is one thing I would be glad to ask you. When a mathematician engaged in investigating physical actions and results has arrived at his conclusions, may they not be expressed in common language as fully, clearly and definitely as in mathematical formulae? If so, would it not be a great boon to such as I to express them so? – translating them out of their hieroglyphics, that we also might work on them by experiment. I think it must be so, because I have always found that you could convey to me a perfectly clear idea of your conclusions, which, though they may give me no full understanding of the steps of your process, give me the results neither above nor below the truth, and so clear in character that I can think and work from them. If this be possible, would it not be a good thing if mathematicians, working on these subjects, were to give us the results in this popular, useful working state, as well as in that which is their own and proper to them?

In effect, Faraday was arguing for the kind of lay summary of papers that is only now becoming widely accepted as a requirement – and to some extent prefigures the success of popular science writing, which became increasingly important as Maxwell's strongly mathematical approach took over physics. As ever, Faraday was a man of vision.

It wasn't just the physicists who wrestled with Maxwell's mathematics. Mathematicians also struggled to understand his work, because he used physical terms rather than familiar mathematical ones to describe what he was doing. The Serbian-American physicist Michael Pupin took a trip to Europe after graduation from his first degree in 1883 to try to get to grips with Maxwell's theory. He started in Cambridge with the intention of speaking to Maxwell himself, not realising that Maxwell was by then dead. He could find no one in Cambridge who seemed capable of explaining the theory to him, getting a satisfactory explanation only when he travelled to Berlin and studied under Hermann von Helmholtz (who apparently did understand the theory).

It would be a long time before there was good experimental evidence that supported the way that Maxwell's model went beyond what had previously been observed. Crucially, his concept of electromagnetic waves, though impressive in its coincidence with the speed of light, needed experimental verification – someone needed to generate waves from an electrical source and demonstrate them crossing space. It would take twenty years before Heinrich Hertz did this with the first artificially produced radio waves.

The beautiful equations

It didn't help that Maxwell's mathematical formulation was decidedly messy. There were a total of twenty equations to cover six different properties such as electrical current and magnetic field strength. The sheer compact power of what Maxwell had done did not become obvious until twenty years later, when the self-taught English electrical engineer and physicist Oliver Heaviside[‡‡‡] (who had been influenced in his work by his uncle, Faraday's friend Charles Wheatstone) used the relatively new mathematics of vector calculus to reformulate Maxwell's equations as just four, stunningly compact lines of text.

These can be presented in a number of ways, depending on the units and whether they take into account a material other than a vacuum, but the simplest version looks like this:

$$\begin{gathered}
\nabla \cdot \mathbf{D} = \rho_{\mathrm{f}} \\
\nabla \cdot \mathbf{B} = 0 \\
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{H} = \mathbf{J}_{\mathrm{f}} + \frac{\partial \mathbf{B}}{\partial t}
\end{gathered}$$

Part of the compactness here is due to the use of ‘operator’ notation. An operator applies a mathematical procedure to every value in a set. So, for instance, if I make up an operator called T which adds 2 to a number and apply it to the positive counting numbers, often called the ‘natural numbers’, the result would be to produce the set 3, 4, 5, 6 … because I started with the natural numbers =1, 2, 3, 4 … and the operator T told me to add 2 to each of them.

The inverted delta operator in the compact version of Maxwell’s equations is usually known as ‘del’ these days, though in Maxwell’s time it was sometimes called ‘nabla’, a term for the symbol suggested to Peter Tait by the theologian William Robertson Smith. The word reflected its shape, deriving from the Ancient Greek term for a type of harp with the same rough outline. Maxwell was never comfortable with this odd-sounding word and regularly mocked it, for example using it to derive a nonsense word in a letter to Lewis Campbell: ‘This letter is called “Nabla”, and the investigation a Nablody.’ At one point, Maxwell wrote to Peter Tait, ‘what do you think of “space-variation” as the name of Nabla?’ We will stick to the modern term, del.

Del indicates differential equations being applied to what could be a whole range of values, either in traditional differential calculus – the sort Newton used – or the vector calculus which Maxwell needed to deal with changing quantities that had both size and direction. Here the dot after the del indicates a particular type of matrix mathematics. (A matrix is just a two-dimensional array of values.) This is imaginatively called the dot product, which produces the ‘divergence’ of a vector field, providing the values of the field at each point. When there is a cross after the del, as in the third and fourth equation, the operation is a ‘cross product’ producing the ‘curl’ of a vector field, which shows the rotation at each point.[§§§]

Between them, the four equations describe the key behaviours of electricity and magnetism. The first,

$$\nabla \cdot \mathbf{D} = \rho_f$$

gives us Gauss’s law. This provides the relationship between the strength of the electrical field[¶¶¶] on the left and the density of electrical charge on the right.

The second,

$$\nabla \cdot \mathbf{B} = 0$$

shows that the magnetic field has zero divergence, which amounts to saying that it is impossible to have an isolated magnetic pole – they always come in pairs that cancel each other out.

The third,

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

is where we get Faraday’s induction explained, providing a mathematical relationship between a changing magnetic field (B) and the electrical field (E) that it produces.

And finally,

$$\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{B}}{\partial t}$$

describes the way that an electrical field produces magnetism. Here H is the ‘magnetising field’, proportional to the magnetic field B, but varying depending on the medium, J reflects the electrical current and the D part of the equation deals with the changing electrical field. Variants on these last two equations combined give all that is needed to describe a wave of changing electric field producing changing magnetic field producing changing electric field and so on, running on at the speed of light.

There is no need to be a physicist or immersed in the workings of the mathematics to appreciate how remarkably compact and powerful is the stark beauty of these four equations (often found in variants on T-shirts), despite their ability to encompass all the phenomena of electromagnetism.

Getting away from it all

Einstein regarded Maxwell as one of the greatest physicists ever – and though Maxwell was probably a better teacher than Einstein, they both suffered from frustration at the way the workload and administration of academic life could eat into their time for getting on with the work that they loved. In Einstein's case, the ideal solution came up with the opportunity to move to the Institute for Advanced Study (IAS) at Princeton in the United States.[||||||] While some academics find that the almost monastic existence in such locations gets in the way of being able to develop new thinking, it was a comfortable workplace for Einstein.

Maxwell had no direct equivalent of the IAS – but he had the advantage of independent wealth. When he had had enough of the pressures of his teaching work at King's, despite the assistant to reduce his lecture commitment, he was able to make the decision to quit his post and return to year-round living at Glenlair with Katherine to work independently. After all, this had proved a great boost to his thinking over the summer breaks and no doubt it could again.

From the view of a modern scientist, Maxwell's action seems a retrograde step. Although science was yet to involve much teamwork, even then there was a great deal of sharing of information, and today's physicists would feel naked without their academic institutions and conferences. Maxwell was moving away from the scientific hubs of the Royal Society and the Royal Institution to the back of beyond in scientific terms. However, he had always relied more on written sources than on face-to-face networking. He was not, in the terms of the time, a particularly clubbable man. As far as we can tell, he took limited advantage of the cultural opportunity of being in London, with no record of him attending a play or a concert or any social event beyond the philosophical gatherings at the Royal Society, the Royal Institution and the BA. The younger Maxwell may have appreciated a wider social sphere, but now Maxwell and Katherine seemed happy with their own company.

There's no doubt that, like Albert Einstein, who moved away from teaching as soon as he could, Maxwell had the potential to benefit from leaving his teaching duties and being able to concentrate solely on his original work. However, unlike Einstein, Maxwell seems to have enjoyed the rewards of bringing the details of physics to others. It could be that his disillusionment with London also arose from the relatively limited scope of his students there. As we saw earlier, many of them only stayed for a little over four terms and saw their education at King's College primarily as a way to bolster careers in engineering and similar fields. There were very few who regarded physics as a serious career option – and it was only the opportunity to work somewhere that took the concept of advancement in physics seriously that would lure Maxwell back to a university some years later.

And so in early 1865, after five fruitful years at King's College, the Maxwells left London to return home to Glenlair. Maxwell could not even wait until the end of the academic year, leaving his assistant and successor, the 'Lecturer in Natural Philosophy' William Grylls Adams,[****] to take over his chair, a position Adams would hold for a further 40 years. Admittedly, Maxwell's retreat from London took some time. To keep up with his commitments outside of King's, giving lectures to working men, Maxwell would spend a few months in his Palace Gardens Terrace home at the end of 1865 and the end of 1866, as well as the early months of 1868, before he gave up the lease. Nonetheless, as far as he was concerned, Maxwell had left academia for ever.

Notes

1 – Maxwell's letter including his speculation on comets and the mechanism of gravity to John Phillips Bond from Glenlair and dated 25 August 1863 is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), pp. 104–9.

2 – The details of Maxwell's viscosity experiment are from James Clerk Maxwell, 'The Bakerian Lecture: On the Viscosity or Internal Friction of Air and other Gases', *Proceedings of the Royal Society of London*, Vol. 15 (1866–67), pp. 14–17.

3 – The efforts the Maxwells went to in order to increase and decrease the temperature of the attic for the viscosity experiments are noted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 318.

4 – Maxwell's letter to Lewis Campbell describing seeing Wheatstone's Stereoscope, written from Edinburgh in October 1849, is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 1 (Cambridge: Cambridge University Press, 1990), p. 119.

5 – Maxwell's notes on an electromagnetic explanation of reflection and refraction based on Jamin's theory are reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 182.

6 – Maxwell's admission that he did not attempt to deal with reflection is quoted in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 3 (Cambridge: Cambridge University Press, 2002), p. 752.

7 – Maxwell's belfry analogy for the use of 'black box' mathematical models is in William Davidson Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1890), pp. 783–4.

8 – Michael Faraday's request that mathematical physicists also give a lay summary of their work is in a letter from Albemarle Street, London, dated 13 November 1857 and quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 290.

9 – Details of Michael Pupin's attempt to understand Maxwell's mathematical explanation of electromagnetism are from Freeman Dyson, 'Why is Maxwell's Theory so hard to understand?', *James Clerk Maxwell Commemorative Booklet* (Edinburgh: James Clerk Maxwell Foundation, 1999), pp. 6–11.

10 – Maxwell's humorous comment about Nabla and Nablody is in a letter to Lewis Campbell written on 19 October 1872, found in William Davidson Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1890), p. 760.

11 – Maxwell's suggestion of using 'space-variation' as a name for Nabla is in a letter to Peter Tait written on 1 December 1873, found in William Davidson Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1890), p. 945.

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[*] This was probably a sneaky dig on the part of Newton. 'Fingo' is not a particularly complimentary way of describing coming up with an idea. His assertion could probably be loosely translated as: 'I'm not going to just make a hypothesis up.'

[†] Literally.

[‡] The same Charles Wheatstone that Faraday filled in for in 1846.

[§] Calotype was the name given to W.H. Fox Talbot's negative-based photography (as opposed to the older daguerreotype process which produced a direct positive image).

[¶] Probably, given this odd structure of the word, this was named for consistency with the farad, the unit of electrical capacitance, named after Michael Faraday. The 'ohm' part is from the German physicist Georg Ohm, who discovered the relationship between electrical voltage and current.

[||] Which is where 'ohmad' came from in the first place. A few years later, the ohm was given the symbol Ω to reflect the convenient assonance between the name ohm and the start of the Greek letter omega.

[**] Maxwell would have had sympathy with the builders of the LIGO gravitational wave observatories in the twenty-first century, which are so sensitive that they can detect the gravitational influence of a passing truck.

[††] To be fair to Maxwell, this is just as well, as the interaction of light and matter could not have been properly understood without quantum theory.

[‡‡] The other contenders were Archimedes and Galileo – Galileo won the debate.

[§§] In other words, as Kant might say, stick to phenomena and forget noumena.

¶¶ Strictly, a hole in the ceiling, from the point of view of the ringers.

|||| What Maxwell means in this rather clumsy wording is that by defining the velocity of this particular rope as 1, they can establish a standard to measure the relative velocities of the other ropes.

*** In physics, ‘degrees of freedom’ means the number of different parameters defining the state of a system – if you know all of these, you can say exactly how it will behave, but if you only know some of them, you will be limited in your ability to predict its response.

††† Maxwell’s great fan Albert Einstein suffered a similar problem initially when he suggested that light consisted of quantum packets of energy or photons, rather than such quanta merely being a way to make the mathematics work. When the leading German physicist Max Planck (whose theory was the starting point for Einstein’s thinking) proposed Einstein for the Prussian Academy of Sciences in 1913, he asked them to overlook the way Einstein ‘missed the target’ with speculation like that over light quanta. This speculation would eventually win Einstein the Nobel Prize when the approach became widely accepted.

‡‡‡ Heaviside is probably best known for the Heaviside layer, familiar to fans of the musical *Cats,* a layer of ionised gas in the upper atmosphere that reflects radio waves, and so allows radio transmission to be sent beyond the horizon (bearing in mind electromagnetic waves travel in straight lines). Heaviside was, to put it mildly, a character, often described as cantankerous and a maverick.

§§§ Remember that Maxwell’s mechanical model involved both linear flows of little spheres and rotation of cells.

¶¶¶ Electrical field is usually represented by an E, but here D is used to represent the ‘displacement’ field that Maxwell referred to in the displacement of the spheres during the ‘twitches’ where his cells twisted elastically.

|||||| Arguably too late, as by the time Einstein moved to Princeton, all his great work was behind him.

**** Adams was later one of the co-discoverers of the earliest form of photoelectric cell.

Demonic Interlude VI

In which the demon suffers a setback

It's entertaining that my creator's new mathematical approach baffled many of his contemporaries, since it represented a step-change in the methods of physicists. Einstein famously had James Clerk Maxwell as one of the few portraits on his study wall, and said of JCM:

> Since Maxwell's time, Physical Reality has been thought of as represented by continuous fields … and not capable of mechanical interpretation. This change in the conception of Reality is the most profound and the most fruitful that physics has experienced since the time of Newton.

The cost of measurement

As far as my progress went, we need to take a leap forward in time to long after Maxwell's death (this is no problem for a demon like me), reaching the 1920s and the work of a young Hungarian physicist, Leo Szilard, whose greatest claim to fame would later be his realisation of how a nuclear chain reaction could work. Remarkably, Szilard would show that JCM's humble demon was in fact a precursor to information theory. To understand Szilard's take on me, you first need to see the other side of the second law of thermodynamics in a little more detail.

As you'll recall, my master and his friends were largely concerned with the second law in terms of heat and the movement of molecules – the whole business of thermodynamics was devised, after all, as a way of getting a better understanding of how steam engines worked. JCM may have made things deliciously probabilistic with his statistical approach – but he was still thinking of the second law being primarily about the way heat never flows from a colder to a hotter body, unless it's given a helping hand. By Szilard's time, though, the dominant aspect of the second law was the way it dealt with entropy.

As I've already mentioned, entropy is a measure of the level of disorder in a system – but it's not as vague a thing as it sounds: it has a clear numerical value. The entropy of a system is based on the number of unique ways you can arrange the components that make up that system.[*] At first glance it's not totally obvious why this is a measure of disorder, but a good example would be the letters of the alphabet. If we put them in the familiar alphabetic order: A, B, C, D … there is just one way to arrange them. But scramble them up and there are many ways to arrange them:

A C B D …
G Q C E …
L A Q V …

… and so on. This means that in alphabetic order, the letters of the alphabet have much lower entropy than they do when they are scrambled up and more disordered, where there are more ways to arrange them.

Szilard believed that for a demon like me to do the job, it would have to be an intelligent being,[†] and that the process of measurement the demon would have to undertake to decide whether or not to let a molecule through would itself result in an increase in entropy which would precisely cancel out the decrease caused by the demon's excellent contribution. The reason that Szilard assumed this to be the case is that the demon has to measure the speed or kinetic energy of the molecule. He then has to store that information in his brain in order to make the decision whether or not to open the door. The business of taking the measurement, Szilard argued, would result in the use of energy and an overall increase in entropy of the system as a whole, as the demon would have to be considered part of the system and his increase in entropy from using energy would be greater than the decrease in entropy in the gas.

It has been suggested that it's not surprising that Szilard came up with a take on my activities that involved me as an intelligent observer, where scientists of Maxwell's day would not have made the distinction. For JCM and friends, the scientist was a totally detached being, an objective observer, entirely separate from the experiment. But by the time Szilard got his hands on me, quantum theory had begun to be developed.[‡]

One essential of quantum physics is that the act of measurement – just looking at something, even – has the potential to have an effect on it. For example, if the demon were to take a measurement of a particle's position using light, that would involve light photons bouncing off the molecule, potentially changing its path and momentum. More significantly still, quantum theory said that until a measurement was made, a quantum particle such as a molecule didn't *have* a position. It could even tunnel its way through my door and appear on the other side.

In Maxwell's approach to statistical mechanics, the probabilities are in the model. All the molecules have a definite position at all times, but we don't know what those positions are, and so we use probability to take a statistical overview of how the collection of molecules is likely to behave. But quantum reality tells us that the positions of the molecules are literally and actually just probabilities until an observation is made. This was the aspect of quantum physics that so worried Einstein, resulting in his famous remarks about God not playing dice. God may not do so – but as for demons …

Taking a quantum physics viewpoint, you can never entirely separate the observer and the experiment. Szilard's big contribution was to make the demon's role part of the overall system of the experiment. My measurements, he suggested, must influence the system in a way that forces the entropy back up just enough to counter any benefits that I had produced.

Although it's not of importance to me, it's interesting to note that Szilard's work on my problem directly led to the American engineer Claude Shannon developing information theory, which introduced the concept of entropy to information, such as the information transmitted from place to place by Maxwell's electromagnetic waves.

As it happens, with true demonic slipperiness, I managed to escape from Szilard's apparent solution to continue to threaten the second law – but that can wait. We need to see how JCM was coping after his move away from the academic world.

Notes

1 – Einstein's assertion that Maxwell made the most profound change in the perception of reality since Newton is taken from Albert Einstein, 'Maxwell's influence on the development of the conception of physical reality', in *James Clerk Maxwell: A Commemorative Volume 1831–1931* (Cambridge: Cambridge University Press, 1931), pp. 66–73.

2 – Leo Szilard's analysis of the demon's measurement and memory storage process is in his paper 'On the Decrease in Entropy in a Thermodynamic System by the Intervention of Intelligent

Beings', in Bernard Feld and Gertrud Weiss (eds.), *The Collected Works of Leo Szilard: Scientific Papers* (Cambridge, MA: MIT Press, 1972), pp. 103–29.

3 – The suggestion that Szilard's consideration of the demon as part of the experiment was influenced by quantum theory comes from Andrew Whitaker's contribution to Raymond Flood, Mark McCartney and Andrew Whitaker (eds.), *James Clerk Maxwell: Perspectives on his Life and Work* (Oxford: Oxford University Press, 2014), p. 183.

4 – Bragg's remark about God running electromagnetics by the wave theory and the devil by quantum mechanics is quoted in Daniel Kevles, *The Physicists* (Harvard: Harvard University Press, 1977), p. 159.

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[*] If you want to get technical, entropy = $k \ln W$, where k is Boltzmann's constant, and $\ln W$ is the natural logarithm of the number of ways the components can be arranged.

[†] I would have thought by now that this went without saying.

[‡] It's not for nothing that the British physicist William Bragg wrote: 'God runs electromagnetics on Monday, Wednesday and Friday by the wave theory, and the devil runs it by quantum theory on Tuesday, Thursday and Saturday.' Nice to see a physicist acknowledging the importance of the demonic contribution to physics, though one does wonder what happened to electromagnetics on Sunday.

Chapter 7

On the estate

One advantage to having control of his own time at Glenlair was the opportunity for Maxwell to focus on writing as well as spending time on his experiments and development of theory. With his old friend Peter Tait, who had stayed as Professor of Natural Philosophy at Edinburgh, Maxwell was assembling a book that was extremely wide in coverage – called *A Treatise on Natural Philosophy,* it was in effect a textbook for the entire physics syllabus at university level. There would arguably not be another physics book that combined such an impressive breadth with being held in such high regard until Richard Feynman's famous 'red books' based on his undergraduate lecture series from the 1960s.

Today, working on a jointly authored book is relatively simple. Not only can chapters and comments fly backwards and forwards by email, collaborators can work on a shared version hosted in the cloud.* For Maxwell and Tait it was a matter of writing letters by hand and waiting for a response in the mail – there was a steady flow of letters back and forth between Glenlair and Edinburgh as the volume came together. In fact, such was the volume of post that Maxwell generated with his wide-reaching scientific correspondence that a post box was installed into the wall of the road by Glenlair for Maxwell's personal use.

Later, Maxwell would also work on solo books on his electromagnetic theory (*Treatise on Electricity and Magnetism*) and a title taking in his own contribution to thermodynamics and a far wider exploration of the subject in the *Theory of Heat,* which was where he exposed to a wider world the 'finite being' that Thomson had turned into Maxwell's demon.

Glenlair life

The demon might never have existed. In 1865, enjoying his first summer at Glenlair that was more than just a vacation, Maxwell had been out riding. He was on an unfamiliar horse[‡] and lost control sufficiently to end up riding fast under low trees. A branch hit him across the head – the injury was little more than a bad scrape, but it became seriously infected with the skin condition erysipelas. With no medical solution other than to keep the patient comfortable and wait for the fever to break, it was touch and go for a few weeks.

Although Maxwell would continue to work – science would never have left his mind for long – being at Glenlair was also an opportunity to have more of a family life. For several years the majority of the Maxwells' time would be dedicated to the place that was always more home than anywhere else. It was a chance to improve the estate and make changes to the house, alterations that had been suggested ever since Maxwell's father's day, but which no one had found time to carry out.

It was also the Maxwells' last chance to have children. Katherine was 41 when they moved to Glenlair full-time. While not impossibly old to have a first child, it was certainly unusually so at the time. There seems little doubt that Maxwell would have loved to have had children, both from the enthusiasm he displayed in playing with the children of others and bearing in mind his sense of duty to the estate, which would have been seen at the time as a responsibility to have an heir. His contemporary biographers note:

> [I]t is impossible not to recall the ready kindness with which, in later life, he would devote himself to the amusement of children. There is no trait by which he is more generally remembered by those with whom he had private intercourse.

As is often the case with spouses of the period, we know a lot less of Katherine's nature, though, as we have seen, there were hints that she was less outgoing than Maxwell. We certainly don't know whether she was interested in children at all, but for whatever reason, it was not to be.

Once Maxwell had recovered from his infection, his time at Glenlair also gave him the opportunity to revisit experiences and modify ideas of the past. Some scientists may be happy to publish a piece of work and then move on, but Maxwell's character seems to have encouraged repeated consideration of a topic, sometimes just fine-tuning what had come before, and at other times – as he had with his electromagnetic model – totally reworking the way he approached the problem.

One opportunity to rework a feature of his younger days was one that many would consider more terrifying than appealing. I am sure I am not alone in having occasional nightmares where I find myself sitting a university exam – in maths or physics – and realise I haven't revised any of it and don't know any of the equations I will need. But when Cambridge University asked Maxwell to take a look at the Mathematics Tripos – the complex and by that time dated exam structure that had brought him to the attention of academia – Maxwell was happy to return to the fray. The exams were mired in the past, unchanged since well before Maxwell had taken them. He was asked to make the content and structure more current and relevant to the modern mathematician, a challenge he took on with enthusiasm.

Back to viscosity

Maxwell was also able to work more on his experiments on the viscosity of gases, with the help of Katherine. All the evidence was that he was correct in thinking that viscosity varied directly with temperature rather than with its square root. But the theory of the time did not support this. As an expert on mechanical models, he realised it was the model itself that was at fault. His first step was to move away from the notion of mean free path (see page 110), which had been useful for getting an idea of the size of molecules, and instead to employ a model where gas molecules exerted force on each other.

This was a significant change to the thinking. To make things simple in his earlier work on kinetic theory, the molecules in the gas had been treated like colliding billiard balls[‡] which head towards each other at full speed until they come into contact, bounce apart, and immediately head away from each other at full speed.[§] With his electromagnetic experience, Maxwell tried instead representing the interaction between the molecules as that of two electrically charged particles repelling each other. Here, the acceleration effects will start earlier as the repulsion acts well before the molecules are in contact and grows rapidly as they come closer with the inverse square of the distance between them.

At the same time, Maxwell threw in another concept, relaxation time, which allows for the way that a system, after being disturbed, returns to a state of equilibrium. Think, for example, of dropping a blob of milk into a cup of tea without stirring it. Before adding the milk, the tea molecules will be in equilibrium, bouncing off each other and keeping the temperature throughout the tea roughly the same. Add the cold milk and there will be a concentration of coldness in one point. The system will have been disturbed. But over time, the milk molecules will disperse through the tea and the tea/milk system will settle down to a new, different equilibrium. The time for the system to undergo this process is the relaxation time.¶

With his modifications to the model of a gas producing its viscosity, Maxwell was now able to match observation and theory. This new version of the model gave a gas a viscosity that was proportional to temperature just as the Maxwells' experiments had shown. It still produced the same velocity distribution for the molecules – his original paper was not wrong in this – but in this new formulation, Maxwell was able to drop one of the limitations of the original model which meant that it would work only if there was no relationship between molecules with particular velocities. He completed this work in 1866 and published it in 1867.

He would revisit his theory six years later, but this was more a matter of tweaking the approach and presentation to match the latest findings from other physicists. He would also present his theory in 1873 to the Chemical Society, where he had to pile in as much evidence as he could for the existence of molecules to justify his use of them. Although chemists made use of the concept, they largely considered molecules to be a useful accounting fiction, rather than actual physical bodies that could perform the complex statistical ballet Maxwell portrayed.

Inevitably, given the gaps in knowledge at the time, there were limitations to the approach that Maxwell took. While his distribution has held up, there were aspects that didn't fit with experimental measurements that were becoming increasingly accurate. This deviation primarily derived from the assumptions Maxwell (and Clausius) made about the ways that molecules could move. Maxwell had dealt with movements in the three dimensions of space and three potential axes of rotation, but he was thinking of the molecules as spheres. We now know that anything more than a single atom has a more sophisticated structure and is capable of rotating in different ways and of vibrating along the bonds between the atoms that make it up. It is this difference from

Maxwell's picture that accounts for the shortfall in his calculations – but given the information he had at the time, it was still a remarkable achievement.

Maxwell made significant progress, particularly in his written output, in his years at Glenlair, but it ought to be stressed that his time wasn't all given over to work. As we have already seen, he spent a considerable amount of effort on improving the estate, and in 1867 he and Katherine took a tour of Italy – still as fashionable a destination for the British well-to-do as it had been in the time of Byron and Shelley some fifty years before. Their trip also got them out of the house while building work was under way, transforming Glenlair into a dwelling that was a little more like a manor house and less like a farmhouse. Being the Maxwells, though, their trip to the Continent was not the classic Grand Tour covering several countries and as many cultural locations as possible with the minimum effort put in by the travellers. The Maxwells made an attempt to learn Italian and seem to have immersed themselves more in the local culture than would have been expected at the time.

Over the years, Maxwell had been able to build up an effective laboratory at Glenlair – certainly sufficient to repeat his experiments on viscosity of gases – but there were some pieces of technology that were beyond the reach of his personal funding. Three years after the retreat to Scotland, he found himself back in London to try to refine his calculation for the speed of electromagnetic waves.

The wine merchant's batteries

As we saw in Chapter 5, back in 1861, on his summer vacation at Glenlair, Maxwell had calculated the expected speed of electromagnetic waves in a vacuum to be around 310,700 kilometres per second, basing his calculation on the equivalent of the two factors used for conventional waves: the elasticity of the medium and its density. The equivalent properties for electromagnetism are known as the magnetic permeability and the electric permittivity of space, and the values of these properties were relatively poorly known at the time, so the result had a significant uncertainty.

With Charles Hockin, an electrical engineer based in Cambridge, Maxwell devised an experiment that would pin down these factors to far greater accuracy than ever before. The experiment balanced out the attraction from the electrical charges on two metal plates with the repulsion between two electromagnets with like poles facing each other. The bigger the effect, the more accurate the measurement could be – which meant hunting down an extremely high-voltage source.

Rather surprisingly, the owner of the most powerful batteries in the country turned out not to be a physics laboratory or an electrical power company, but a wine merchant based in Clapham, London. John Gassiot had spent his fortune on constructing an extravagant private laboratory. It was Gassiot who provided Maxwell and Hockin with a vast battery of cells, 2,600 in all, which between them put out around 3,000 volts.

The experiment proved highly successful, though the batteries went flat with unnerving rapidity, meaning that Maxwell and Hockin had to take measurements furiously quickly before the charge ran out. These more accurate values for magnetic permeability and the electric permittivity resulted in a calculated speed for electromagnetic waves of 288,000 kilometres per second (kps).

In the original calculation, Maxwell had come up with 310,700 kps to Fizeau's 314,850 kps – so it might seem that his new calculation put him further off the mark. But in the intervening period, Maxwell had learned of an updated value for the speed of light from another French experimenter, Léon Foucault.[‖] Foucault had used an improved version of Fizeau's equipment to get a more accurate speed of 298,000 kilometres per second[**] – and so Maxwell's waves now seemed even more certain to be light.

This was immediately a useful support to his theory, but in other cases the significance of the work that Maxwell did would not become clear until much later. As we will see below, even a spin-off from Maxwell's work could hold promise of great things – simply because he retained his child-like curiosity, seeing what others would regard as everyday phenomena and realising that here was something special and worth investigating.

Meet the governor

As we have seen, when Maxwell had been working on the electrical resistance standard at King's College (page 183), his colleague Henry

Fleeming Jenkin had designed a governor to keep a coil rotating at constant speed. Governors would be familiar to anyone who had seen a static steam engine. The early days of steam were riddled with explosions and runaway catastrophes when poorly understood technology was used outside its operating parameters. Back in the 1780s, James Watt had come up with the centrifugal governor. This elegant device has a pair[††] of weights on hinged bars, which fly outwards as the vertical spindle they are mounted on rotates. The faster the spindle goes, the further out the balls move. The hinged bars are linked to a valve, closing it off if the balls fly too far out from the centre. This means that a steam engine with the governor in place never runs too fast – it automatically shuts itself off over a certain speed.

Thinking more about Jenkin's governor, Maxwell began to explore the different ways in which this form of feedback mechanism, which automatically regulates a process, could be deployed (another, more modern version of a feedback-based governor present in almost all homes now is the humble thermostat). In 1868, Maxwell wrote a paper named *On Governors* which, with his usual thoroughness, gave the process a mathematical treatment. In fact he pointed out that, at least by his definition, Watt's device wasn't a governor at all.

In the paper, Maxwell made the distinction between a 'moderator', in which the correction that is applied grows with the excess speed, and a 'governor', which also involves the integral of the speed.[‡‡] He showed mathematically that only a governor with this facility would exactly regulate the speed. A moderator, like Watt's, would still provide negative feedback, but could not give the exact value required to balance out the error.

The mathematics Maxwell used here drew on some of his work on Saturn's rings – getting a governor right was the same kind of problem, in the sense that it involved the stability of a system. Ironically, his work on stability in governors would be generalised by another Cambridge mathematician, Edward Routh, who won the Adams Prize (checked by Maxwell) for his work, just as Maxwell had for his analysis of the rings of Saturn.

Decades later, this paper by Maxwell would be recognised by the American mathematician Norbert Wiener, who in the 1940s originated the concept of cybernetics[§§] – the use of systems with communication and feedback that would become important in control systems, engineering and computer science. Wiener considered Maxwell the father of automatic controls, providing the first steps in the development of the control systems theory that lies behind everything from cruise control on cars to the systems that keep nuclear power stations safe.

Thinking in four dimensions

Sometimes the work that Maxwell did would have greater impact than was perhaps even intended. In his *Treatise on Electricity and Magnetism,* he took the first major step that would enable Oliver Heaviside to produce the compact versions of his equations. This was because Maxwell had become interested in quaternions, a relatively obscure mathematical device introduced by the Irish mathematician Sir William Hamilton (not to be confused with his contemporary, the Scottish philosopher Sir William Hamilton, whose lectures Maxwell attended while at Edinburgh University).

By the 1860s, most scientists were comfortable with the concept of complex numbers, which incorporated values in two dimensions at once. A complex number is an ordinary number combined with an imaginary number – a multiple of i, the square root of –1. So, for example, a complex number might be $3 + 4i$. These numbers can be manipulated just like an ordinary number, and map onto a two-dimensional graph with the real numbers on one axis and the imaginary numbers on the other.

Complex numbers proved highly useful when dealing with anything that has the form of a wave, which has both its position in a particular direction and an amplitude that varies with time. However, many physical processes take place not in the flat plane of graph paper but in three spatial dimensions. Quaternions provided a mechanism for dealing with values that had amplitude and a three-dimensional location. This was done by having effectively three different imaginary components, so a single quaternion might look like $3 + 4i + 2j + 6k$.

Hamilton thought, correctly, that quaternions had the potential to revolutionise the mathematics of physical processes, but the approach proved difficult to handle and instead a different mechanism to deal with values that varied in multiple dimensions, vector analysis, was developed.

Maxwell provided the bridge between Hamilton and practicality – inspired by quaternions, he came up with the terms ‘convergence’, ‘gradient’ and ‘curl’ to represent different forms of quaternion operation which would be carried through into vector calculus, though ‘convergence’ was replaced by its opposite ‘divergence’, and the longer names shortened, ending up with the operations div, grad and curl (two of which are seen in Heaviside’s formulation of Maxwell’s equations on page 193).

We can see a typical Maxwellian delight in words in the way that he worked towards the term ‘curl’, first in a letter to Peter Tait, where it was just an alternative to ‘twist’, and then in a paper written for the London Mathematical Society in 1871 when he had finally settled on curl.

The letter begins by asking if Tait called the mathematical operator that would be known as del ‘Atled’ (it is an upside-down delta). He then wrote:

> The scalar part I would call the Convergence of the vector function and the vector part I would call the twist of the vector function. (Here the word twist has nothing to do with a screw or helix. If the words *turn* or *version* would do they would be better than twist for twist suggests a screw.) Twirl is free from the screw motion and is sufficiently racy. Perhaps it is too dynamical for pure mathematicians so for Cayley’s[¶¶] sake I might say Curl (after the fashion of Scroll).

Confusingly, after saying this, Maxwell goes on in the rest of his letter to refer to the vector part as the twirl.

By the time he got to his Mathematical Society paper, though, he had decided to go with his proposal to satisfy the mathematicians:

> I propose, but with great diffidence, to call this vector the ***Curl*** of the original vector function. It represents the direction and magnitude of the subject matter carried by the vector. I have sought for a word that shall neither, like ***Rotation, Whirl,*** or ***Twirl,*** connotate motion, nor, like ***Twist,*** indicate a helical or screw structure which is not of the nature of a vector at all.

The life academic

It might seem that everything was going swimmingly at Glenlair. Maxwell wrote the first of his definitive books, undertook experiments, and developed theory. His family life was everything he had hoped for with the exception of having children. And he had said on leaving London that he would never return to academia. Yet perhaps he also felt that there was something missing from his life. He could discuss his work with Katherine and could exchange ideas with other scientists in letters, but it wasn't the same as having lively discussion with other experts in the field. Maxwell seems to have missed the opportunity for broader intellectual exchange.

The first opportunity that tempted him to think of getting back into the academic world was when the post of Principal at Scotland's oldest university, St Andrews,[‖‖] came up in late 1868. Maxwell wavered on whether to apply. In a letter to William Thomson at the end of October he wrote:

> One great objection is the East Wind, which I believe is severe in those parts. Another is that my proper line is in working not in governing, still less in reigning and letting others govern.

Four days later it seemed as if Maxwell had made up his mind. He wrote to Lewis Campbell:

> I have given considerable thought to the subject of the candidature, and have come to the decision not to stand. The warm interest which you and other professors[***] have taken in the matter has gratified me very much … but I feel that my proper path does not lie in that direction.

Yet after another four days, Maxwell had clearly reversed his decision and began writing to contacts to try to win support for this political appointment, particularly any he felt could influence the Home Secretary, the magnificently named Gathorne Gathorne-Hardy. By 9 November he was writing to Thomson:

> When I last wrote, I had not been at St Andrews. I went last week and have gone in for the Principalship. If you can certify me having been industrious &c since 1856, or if you can tell me what scientific men are conservative[†††] or still better if you can use any influence yourself in my favour pray do so. 6 Professors out of 9 [at St Andrews] have memorialized the Ld Adv. & Home Sec. for me together with Principal Tulloch the V. Chancellor. Of the other 3, one Prof Shairp is a candidate and one, Prof. Bell does not approve of memorials at all and is neutral.

Despite the apparent support of the resident professors, it was not to be. Although the post was rumoured to be due to go to a 'man of science', it may have been that Maxwell's lack of administrative experience counted against him with the political decision-makers. But this did not mean that Maxwell would remain at Glenlair for the rest of his working life. When, a few years later in 1871, he was approached with the offer of a new post that would truly wrench physics away from the medieval concept of natural philosophy and bring it to the forefront at a great university, Maxwell, pushed out of his stay-at-home frame of mind by the opportunity at St Andrews, decided it was time for a fresh challenge.

Notes

1 – Maxwell's fondness for entertaining children is described in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 40.

2 – Norbert Wiener's reference to Maxwell as the father of modern automatic control is noted in Rodolphe Sepulchre, *Governors and Feedback Control*, available at: www.clerkmaxwellfoundation.org/Governors.pdf

3 – Maxwell's letter to Peter Tait, written from Glenlair on 7 November 1870, on the naming of the mathematical term that would be called 'curl', is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), pp. 568–9.

4 – Maxwell's introduction of the mathematical term 'curl' is from James Clerk Maxwell, 'Remarks on the Mathematical Classification of Physical Quantities', *Proceedings of the London Mathematical Society*, s1–3 (1871), pp. 224–33.

5 – Maxwell's letter to Thomson from Glenlair dated 30 October 1868, citing the east wind as a reason not to apply for a post at St Andrews, is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), pp. 457–9.

6 – Maxwell's letter to Campbell from Glenlair dated 3 November 1868, saying he would not stand, is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 460.

7 – Maxwell's letter to Thomson from Glenlair dated 9 November 1868 saying he would stand is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 463.

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[*] And, yes, once again, Maxwell's scientific discoveries are fundamental to our ability to be able to do this.

[†] We're not sure why. Perhaps his usual mount was lame.

[‡] Physicists love billiard balls as models – no doubt a sign of misspent youths.

[§] Real billiard balls are not like this – they are not perfectly rigid, so they deform as they come into contact, giving a short period of acceleration in an impact that isn't instantaneous, and they lose energy to heat and sound, but physics models often involve simplification to make the mathematics manageable.

[¶] Stirring the tea changes things again, reducing the relaxation time for the distribution of temperature but introducing a new disturbance in the form of a vortex. Who would have thought a cup of tea involved so much physics?

[||] Foucault is probably best known for his pendulum, which changes its direction of swing with the Earth's rotation (and gave Umberto Eco a good title for a book).

** The speed of light has now been fixed at 299,792.458 kilometres per second, as the metre is defined as 1/299,792,458th of the distance light travels in a second.

†† A single weight would do the job, but would be unstable – having a pair enables them to balance each other out.

‡‡ The integral, one of the main vehicles of calculus, here gives the area under the curve of a graph of the changing speed of the governor – in this case reflecting the displacement of the governor, rather than the measured speed. This enables the governor to bring the speed to the required value however large the variation, whereas with a moderator, speed will still increase, but less so than if the moderator was not there.

§§ ‘Cybernetics’ and ‘governor’ are both from the same Greek root, meaning a steersman, but governor was distorted in passing through a Latin version of the word.

¶¶ Arthur Cayley, an English mathematician, at the time the Sadlerian Professor of Pure Mathematics at Cambridge.

|||| To be precise, the position was Principal of the United College of St Salvador and St Leonard in the University of St Andrews.

*** Campbell was, at the time, Professor of Greek at St Andrews.

††† Gathorne-Hardy was a member of the Conservative government, which was probably why Maxwell said this, though Maxwell was also by nature conservative with a small c.

Chapter 8

Cambridge beckons

The approach that would signal the beginning of the last great phase of Maxwell's scientific life came from the University of Cambridge. Although Cambridge had proved a mathematical inspiration and remained in many ways an academic spiritual home to Maxwell, it was not at the time the most advanced British establishment in terms of the sciences. However, the chancellor of the university was determined to change this.

The Cavendish connection

Unusually for the nominally top person in a university (even today), the Cambridge chancellor had scientific leanings. Like Maxwell, he had been an outstanding mathematician of his year, becoming Second Wrangler and winning the prestigious Smith's Prize. What's more, the chancellor was the grand-nephew of Henry Cavendish, another Cambridge graduate, who had been one of the leading scientists at the end of the eighteenth century. Henry Cavendish had played a significant part in the establishment of the Royal Institution and had undertaken the first experiment to provide a reasonable measurement of the density of the Earth, making it possible to calculate for the first time Newton's gravitational constant, G.

The current Cambridge chancellor was also a Cavendish – William Cavendish, the Duke of Devonshire – an extremely rich man, who, as a politician, had served on the Royal Commission on Scientific Education, set up among concerns that the country was falling behind its competitors in scientific prowess. Cavendish was prepared to donate a large sum to the university on the understanding that it built a physics laboratory and endowed a chair of experimental physics.

In the quaint terminology of the time, the Chair of Experimental Physics was founded by a Grace of the Senate on 9 February 1871 stating that ‘the principal duty of the professor is to teach and illustrate the laws of Heat, Electricity and Magnetism; to apply himself to the advancement of the knowledge of such subjects; and to promote their study in the university’. This meant that the university was on the hunt for a dynamic, world-class physicist, with the dual role of becoming the first Cavendish Professor and supervising the construction of a leading-edge laboratory. The first people to be approached were Maxwell’s old friend, William Thomson, and the German physicist Hermann von Helmholtz, who like Maxwell did significant work on electromagnetism and thermodynamics.

However, Thomson did not want to leave Edinburgh and was concerned at the limited support available in Cambridge from instrument makers, an essential if the laboratory was to be successful. Helmholtz, at the time based in Heidelberg, was just in the process of negotiating a post in Berlin, the mathematical capital of Europe. As a result, Maxwell received a letter in mid-February 1871 from Edward Blore at Trinity College:

> My Dear Maxwell
> Our Professorship of Experimental Physics is now founded & though the Salary is not magnificent (£500 a year) yet there is a general wish in the university that this branch of Science should be supported in a way creditable to the University. The Duke of Devonshire has undertaken the expense of the building & Apparatus, & it remains for us that we should appoint the Professor. Many residents of influence are desirous that you should occupy the post hoping that in your hands this University would hold a leading place in this department. It has, I believe, been ascertained that Sir W. Thomson would not accept the Professorship. I mention this in case you should wish to avoid the possibility of coming into the field against him.

Maxwell knew he was not the first choice. He replied immediately to Blore, saying:

> Though I feel much interested in the proposed chair of Experimental Physics I had no intention of applying for it when I got your letter, and I have none now unless I come to see that I can do some good by it.

He went on to ask details of the job – the duties, who made the appointment, how long he would be expected to serve, how many terms a year and so forth. The details were sent to Maxwell three days later by George Stokes, the Lucasian Professor at Cambridge, and within a week Maxwell had decided to stand.

Maxwell was elected to the post on 8 March 1871. Or, more accurately, he was appointed. The professorship was in principle in the hands of the Senate of the university. Strictly speaking, this comprises all holders of an MA or higher degree from the university, plus significant officers such as the Vice Chancellor, but in practice it would have been just those resident at the time. Of around 300 members, only thirteen voted – not entirely surprisingly, as they were only offered a single choice. The decision was clearly made behind the scenes, based on approaches to key figures.

Cambridge was lucky to end up with Maxwell, as neither of his rivals had his practical experience of running an estate alongside his excellence in physics, which would surely have helped when it came to managing the construction project – though as Maxwell pointed out in his letter to Blore, Thomson had practical experience of running a university laboratory, which he did not. In March 1871, Maxwell took a tour of the few existing physics laboratories in the UK, picking up the best practice to pull together in designing the new facility.

A different professor

It's interesting to think for a moment about why James Clerk Maxwell was offered this particular position, how he saw his role, and how his ideas might have been shaped by his experiences in London. At first sight, this master theoretician might not seem the ideal candidate to become professor of *experimental* physics, but we need to remember that Maxwell had proved a more than capable experimenter, and one who was prepared to go the extra mile and set up laboratories in his home both in London and at Glenlair when nothing was available otherwise. He had also remained in close contact with Cambridge since leaving King's College London, helping to reform the Mathematics Tripos examination system in 1866 and 1867.

The mix of talents that he could bring to Cambridge is reflected in a letter to Maxwell from John Strutt (Lord Rayleigh) who would go on to replace Maxwell as Cavendish Professor on his death. Among other things, Rayleigh discovered the element argon and explained why the sky is blue. Rayleigh wrote:

> When I came here [Cambridge] last Friday I found every one talking about the new professorship, and hoping that you would come … There is no one here in the least fit for the post. What is wanted by most who know anything about it is not so much a lecturer as a

> mathematician who has actual experience in experimenting, and who might direct the energies of the younger Fellows and bachelors into a proper channel.

In his inaugural lecture at Cambridge in 1871, Maxwell remarked that the new laboratory would be worthy of the university if 'by the free and full discussion of the relative value of different scientific procedures, we succeed in forming a school of scientific criticism, and in assisting the development of the doctrine of method'. For Maxwell neither the Ancient Greek approach of armchair philosophising which had dominated universities until Newton's day, nor the pure mechanical experimental approach that had driven the industrial revolution was the way forward.

In his vision of the future of physics, Maxwell saw a close, symbiotic partnership between experiment and the development of theory – neither should operate in isolation. Arguably, a major factor in developing this viewpoint (leaving aside how closely it reflected the interaction of experiment and theory in his own working life) was the downside of the engineering-dominated approach at King's. Although Maxwell had nothing against practical, applied science, he saw clearly that it was necessary to move away from industry-driven goals and to be able to address the fundamentals.

It was also clear to Maxwell that something needed to be done about the Cambridge syllabuses. As we have seen, he was involved a few years before his appointment in the redesign of the Mathematics Tripos, helping to expand it beyond its old topics to take in more modern aspects of physics, such as electricity, magnetism and heat – and he would write a major textbook, the *Treatise on Electricity and Magnetism,* to support this. Now he had the chance to make sure that the broadest modern physics curriculum was covered with the introduction of experimental physics to Natural Sciences – though he was still constrained also to include elements of physics in the Mathematics Tripos.

Along with other supporters of laboratories in universities, his approach was in the vanguard of transforming experimental physics from simple observation to making measurements to support or dispose of theories. In his opening lecture, Maxwell first pointed out the limitation of making more and more accurate measurements with no extension of theory.

> The characteristic of modern experiments – that they consist principally of measurements – is so prominent that the opinion seems to have got abroad that, in a few years, all the great

> physical constants will have been approximately estimated, and that the only occupation which will then be left to men of science will be to carry these measurements to another place of decimals.[*]
>
> If this is really the state of things to which we are approaching, our Laboratory may perhaps become celebrated as a place of conscientious labour and consummate skill; but it will be out of place in the University, and ought rather to be classed with the other great workshops of our country, where equal ability is directed to more useful ends.

Then, however, Maxwell went on to show his faith in there being far more to come: ‘But we have no right to think thus of the unsearchable riches of creation, or of the untried fertility of those fresh minds into which these riches will continuously be poured.’ He pointed out that even when progress has largely been about polishing the decimal points, science ‘is preparing the materials for the subjugation of new regions, which would have remained unknown if she had been contented with the rough methods of her early pioneers’.

He realised that no university was better positioned to do this than Cambridge – an institution that has gone from strength to strength since Maxwell’s appointment, so that it is now one of the world’s leading universities for physics. This is likely to be part of the answer to a second question about the appointment, which is why Maxwell would have accepted, having voluntarily given up his position in London. It seems unlikely that the attraction of Glenlair would ever have palled for him. But the opportunity in Cambridge to set in motion something that could be transformative for the physics he loved was simply too great. And, just in case it didn’t work out too well, he put himself forward on the understanding that he would not have to stay in post for longer than a year.

Engraving of Maxwell from c. 1890, taken from an 1870s photograph by Fergus of Greenock.
Getty Images

The last second home

The Maxwells set up a new second home in Cambridge in the spring of 1871 (this despite an off-putting letter from George Stokes who wrote, 'I am afraid you will find a good deal of difficulty in getting a house in Cambridge. The supply is hardly equal to the demand.'). Somewhat less imposing than his London residence, 11 Scroope Terrace was (and remains) a handsome three-storey townhouse. The Maxwells would spend the university terms and Christmas vacation at Scroope Terrace for the rest of Maxwell's life, returning to Glenlair for the warmer summers.

The new position of Professor of Experimental Physics was not initially an idea fit for the complex structure of Cambridge University, where the individual colleges were bodies with considerable power in their own right. At the time, the vast majority of the teaching load fell on college lecturers and private tutors. Although there were a number of university professorships, they were set up by individual endowments each with their own set of rules, though those rules had become at the least bent over the years – so, for example, the Lucasian Professor of Mathematics, a position held by Isaac Newton and more recently by Stephen Hawking, has almost from the beginning tended to have more of a theoretical physics orientation than was perhaps first envisaged.

When Maxwell took his university position, some colleges had lecturers covering physics already, so he found himself to an extent in competition, with the added negative factor that students were generally expected to pay to attend lectures outside their college. Over time, the system was improved to pull together the college and university lecturing so that eventually it reached the stage where lectures were provided by the professors and lecturers of the university, while the colleges provided tutorials in the form of 'supervisions' – but during Maxwell's time this was a system in transition, making a more difficult fit for his role within the university's structure.

It didn't help that while the university recognised that someone in Maxwell's position should not be over-burdened with actually giving lectures, expecting most of his time to go on his own research and administration, the glacially slow university administration did not make it easy for Maxwell to take on an assistant lecturer or 'demonstrator'. Before there was even a building to give a lecture in, Maxwell did suggest one John Hunter for the post, but the university seems to have shown little interest in the appointment.

It was possibly just as well, as Hunter was not in good health (he died a year later), though he did have an appropriate background as he had worked with both Thomson and Tait and had held his own professorial chair at Windsor College, Nova Scotia until he found the low temperatures there unbearable. But Maxwell seems to have suggested him more on the strength of their Scottish connection than any familiarity with Hunter's skills. He wrote to his friend Peter Tait, who knew Hunter better:

> I only know him as the man who charges charcoal with bad smells.[†] Would he be a good demonstrator at Cambridge? I have no doubt that a man who could occlude a fishy fume in a burnt stick could also floor a demon,[‡] which I suppose to be the essential part of the office.

In the end, the first demonstrator, a recent Cambridge graduate called William Garnett who was later Maxwell's joint biographer with Lewis Campbell, would be appointed in 1874.

There was also the difficulty of winkling the components of physics out from the other subjects to construct a separate discipline. At the time, what we would now consider to be physics was largely housed within the Mathematical Tripos, but parts of it also were found in the Natural Sciences Tripos, which covered chemistry, mineralogy, geology, botany and zoology. Physics would end up as a separate discipline in the Natural Sciences Tripos, taking to itself the parts of chemistry that dealt with heat and electricity (and later the structure of atoms and molecules) and adding in many of the areas previously considered as part of mathematics, such as the science of moving bodies and astronomy.

Even today, the split is not entirely clear at Cambridge. Experimental physics sits firmly in the Natural Sciences side, but the Department of Applied Mathematics and Theoretical Physics (for many years the academic home of Stephen Hawking) straddles Natural Sciences and Mathematics.

The power of the Mathematics Tripos was considerable. Senior Wranglers were feted as national heroes, with their school and home town often having a holiday or procession to celebrate their achievement. This meant that the best minds were reluctant to stray from Mathematics into what were considered the less stellar regions of Natural Sciences. (When Maxwell arrived at Cambridge, Natural Sciences could not offer an honours degree, which was only available in Mathematics and Classics.)

George Bettany, a Natural Sciences graduate from Maxwell's day, wrote in *Nature* in 1874:

> The great hindrance to the success of the Cavendish Laboratory at present is the system fostered by the Mathematics Tripos. The men[§] who would most naturally be the practical workers in the laboratory are compelled to refrain from practical work if they would gain the best possible place in the [Mathematics] Tripos list. Very few have courage so far to peril their place or to resign their hopes as to spend any valuable portion of their time on practical work.

It would take a good fifty years for the differences and difficulties of the split to be fully resolved, and the relative importance of the Mathematics and Natural Sciences Tripos to be rebalanced, though throughout that period, with the work of one of Maxwell's successors, J.J. Thomson,[¶] and others, it became impossible to ignore the importance of experimental physics.

The very need for a physical laboratory also took some accepting in a university that considered it somehow to question the sanctity of intellect if it were necessary to resort to experimental proof. As Maxwell's Cambridge contemporary, the mathematician Isaac Todhunter, remarked of the science student:

> If he does not believe the statements of his tutor – probably a clergyman of mature knowledge, recognised ability, and blameless character – his suspicion is irrational, and manifests a want of the power of appreciating evidence.

By the time Maxwell was appointed, Edinburgh, Glasgow, London, Manchester and Oxford had physics teaching laboratories, though only Glasgow under William Thomson and Oxford under a Professor Clifton had new buildings that had been designed for the purpose, which Maxwell wasted no time in visiting.

Ancient lights and modern physics

The site chosen for the new Cambridge laboratory was, frankly, not ideal.[‖] For a number of years, the site of the former Botanic Gardens in central Cambridge had been gradually taken over as a hub for most of the other natural sciences, forming what is now known as the New Museums Site. This seemed the logical location for Maxwell's laboratory, but the remaining free space there was very limited. The new laboratory would loom across the narrow Free School Lane so tightly that Corpus Christi College, on the opposite side of the lane, claimed a loss of ancient lights and made a failed attempt to sue the university.

Maxwell engaged a relatively unknown architect, William Fawcett, whose experience to date had largely been in church architecture, though Maxwell seems to have damped down Fawcett’s enthusiasm for Gothic frills; the architect largely limited his flights of fancy to the decorated main gate, carrying the Cavendish coat of arms, a statue of the Duke and the biblical inscription *Magna opera Domini exquisita in omnes voluntates ejus* (‘The works of the Lord are great: sought out of all them that have pleasure therein’ – Psalm 111, verse 2).

Despite the limitations of the site, Maxwell’s design for the Devonshire building, as it was initially called, proved a triumph, with experimental physics underway three years after Maxwell was brought on board, and lectures starting in October 1872 before construction was finished. Maxwell wrote to Lewis Campbell on 19 October 1872:

> Lectures begin 24th. Laboratory rising, I hear, but I have no place to erect my chair, but move about like the cuckoo, depositing my notions in the chemical lecture theatre 1st term; in the Botanical in Lent and in Comparative Anatomy in Easter.

An interesting insight into Maxwell’s thinking can be obtained in an extract from a letter to Katherine written on 20 March 1871, where he observed:

I think there should be a gradation – popular lectures and rough experiments for the masses; real experiments for real students; and laborious experiments for first-rate men like Trotter, Stuart and Strutt.

The next day, Maxwell wrote to William Thomson, one of the few physics professors in the UK to already have a laboratory, asking for his opinion on the requirements for ‘material accommodation’. Maxwell provided Thomson with a list for his consideration which gives us an effective insight into the kind of facilities the Cavendish would provide:

> Lecture room *taken for granted.*
>
> Place to stow away apparatus d^{O}.[**]
>
> Large room with tables &c for beginners at experiments, gas and water laid on &c.
>
> A smaller place or places for advanced experimenters to work at experiments which require to be left for days or weeks standing.
>
> A place on the ground floor with solid foundations for things requiring to be steady.
>
> Access to the roof for atmospheric electricity.
>
> A place with good ventilation to set up Groves or Bunsens batteries without sending fumes into the apparatus.
>
> A good Clock in a quiet place founded on masonry, electric connexion from this to other clocks to be used in the expts and from these connexion to machines for making sparks, marks on paper &c.

> A well constructed oven, heated by gas to get up to a uniform high temperature in large things.
>
> A gas engine (if we can get it) to drive apparatus, if not, the University crew in good training in four relays of two, or two of four according to the nature of the exp^t.[††]

For his ‘popular lectures’, Maxwell would build a 180-seater lecture theatre, for the dedicated experimental physics students a teaching laboratory with ten workbenches … and for the ‘firstrate men’ a number of smaller rooms where they could run their experiments undisturbed by the hurly-burly of undergraduate experimental sessions. It was in the detail of designing these spaces that Maxwell really led the field. For example, the lab workbenches were cushioned from the floor to prevent vibration from influencing experiments. Metal pipes were always visible so that those undertaking electromagnetic experiments could avoid them, and a vacuum system was available throughout the building. Cast iron hollow bricks were built into the walls at intervals to support apparatus, while ceiling joists had to protrude through the plaster so that supports could be fixed to them. There were even especially wide external window ledges, still visible on the building, so that heliostats – devices that tracked the Sun and kept a supply of bright light flowing into the building – could be stationed on them.

Maxwell’s suggestion of enabling the serious scientists to have separate facilities seemed very much in line with the thinking of Coutts Trotter, the Trinity College physics lecturer, who wrote to Maxwell in April 1871:

> There is no doubt much to be said for natural selection[‡‡] but will not the struggle for existence between the men who want the rooms darkened and the men who want their rooms light, the men who want to move about magnets and the men who want to observe galvanometers be unduly severe?

A concern for this kind of conflict comes through in the way that Maxwell organised the smaller rooms by the type of measurement required, to avoid interference between experimental needs, rather than the traditional topic orientation used in earlier laboratories.

A slow start

The Cavendish Laboratory – the name change was suggested by Maxwell to commemorate both Henry Cavendish and their present-day benefactor

– was officially opened in June 1874 and helped Cambridge to become Britain's leading university for work in physics. During the next hundred years, many major developments from splitting the atom to the discovery of the structure of DNA would occur in Maxwell's laboratory.

It would be unfair, though, to suggest that the Cavendish under Maxwell went from nothing to a thriving establishment overnight – and some clearly doubted Maxwell's ability to make a difference. It's notable that an 1873 editorial in the journal *Nature* did not hold out a lot of hope for the Cavendish:

> Let any one compare Cambridge, for instance, with any German university; nay, with even some provincial offshoots of the University in France.[§§] In the one case he will find a wealth of things that are not scientific, and not a proper laboratory to work in; in the other he will find science taking its proper place in the university teaching, and, in three cases out of four, men working in various properly appointed laboratories, which men are known by their works all over the world.

Although Maxwell laid the foundations for the future success of the Cavendish, the laboratory was constantly underfunded during his tenure. He could not, for example, afford the essential services of a technician full-time – once a Robert Fulcher had been assigned to the post in 1877, it was on a freelance basis that soon saw Maxwell losing much of Fulcher's time to other departments.

Initially there was no real system to the teaching – lectures and classes were provided, but that was not a clear experimental physics component to the undergraduate Natural Sciences degree. Each year, though, Maxwell did deliver a lecture course, covering heat and matter in the first (Michaelmas) term, electricity in the second (Lent) term and electromagnetism in the third (Easter) term. The content of the later lectures seems to have been based on his *Elementary Treatise on Electricity,* which became a widely-used textbook.

Despite the large laboratory being built for teaching purposes, it was primarily used so that anyone available – whether undergraduates or not – could contribute to the boring parts of research on behalf of the senior physicists – for example, in Maxwell's ongoing attempts to standardise electrical units. It was only around 1879, with numbers on the undergraduate course rising to around 30, that regular practical experimental physics classes were implemented.

Similarly, there was at the time no good structure to support postgraduate staff in the laboratory. It was hard to get a college fellowship based on a scientific subject, and when they were obtained they rarely lasted long (as had been the case with Maxwell's own fellowship at Trinity – though he would have been seen as a mathematician). The position of fellow was often thought of as a stepping stone to a more significant position. It could only be held by unmarried men, and anyone staying on longer than seven years had to be ordained in the Church of England.

When postgraduates started to become more common after Maxwell's time they mostly had the more respectable Mathematics degrees, which made it easier to get a fellowship position than a degree in Natural Sciences. At the time the whole system was biased in this direction. Experimental physics, even then, required more assistance than did the lonely work of the mathematician. But college fellowships went primarily to those who produced an outstanding dissertation in the Mathematics Tripos, and this was obliged to be a solo piece of work. It would be a few decades before the Cambridge system fully accepted the need to bring through post-doctorate students and fellows from the Natural Sciences Tripos.

Women in the laboratory

Despite his support for Katherine helping with his work when at home, Maxwell was a man of his time and he was initially extremely doubtful about allowing women students into the laboratory. The first women's college at Cambridge, Girton, had been established remotely in Hitchin in 1869 and opened at Girton on the outskirts of Cambridge in 1873, though initially the students were not members of the university. A striking illustration of the way that women were treated in the university is the way they were dealt with in respect of the Wrangler listing for the Mathematics Tripos.

As we have seen, the position of Senior Wrangler was of huge importance across the country, but the position could not be given to a woman. Women first appeared in the Tripos listings in 1882, but rather than awarding them the position of a specific Wrangler they would be classed as fitting, say, 'between the 9th and 10th Wranglers'. In 1890, Philippa Fawcett, who would later be one of the first female lecturers in mathematics, was listed as 'above the Senior Wrangler' – so was, in fact, entirely deserving of that coveted position, but could not be awarded it.[¶¶]

Maxwell would not give permission for women to use the Cavendish for several years. Around 1874 he wrote a pair of poems[||||] with the title 'Lectures to Women on Physical Sciences', the first about a woman participant in science, the second regarding a woman lecturer. The first introduces us to a class with one (female) member, located in a small alcove with dark curtains. The woman in this practical class is taking a reading from a Thomson mirror galvanometer, which gives Maxwell a chance to contrast his concerns about inaccuracy of measurement with the classical description of women in poems of the time:

O love! you fail to read the scale
Correct to tenths of a division
To mirror heaven those eyes were given,
And not for methods of precision.

Eventually, in the mid-to late 1870s, Maxwell changed his mind on women being allowed into the building, though even then this seems to have been grudging. His assistant Garnett noted:

> At last [Maxwell] gave permission to admit women during the Long Vacation,[***] when he was in Scotland, and I had a class who were determined to go through a complete course of electrical measurements during the few weeks when the laboratory was open to them.

The first true class for women in experimental physics began in 1878, and women would not be admitted to the main Natural Sciences physics course until the time of Maxwell's successor as Cavendish Professor, Lord Rayleigh.

Even so, Maxwell had done a remarkable amount to improve the standing of physics at Cambridge – and raised his own profile with that of the Cavendish Laboratory. Maxwell ensured that his position of Cavendish Professor of Experimental Physics would be passed on (there was some uncertainty as to whether it should be a one-off position initially). It is a chair that has continued to this day, with just nine individuals so far holding the post. These have included several of the 'big beasts' of physics, including J.J. Thomson, Ernest Rutherford and

William Bragg[‡‡‡] (the younger of the Bragg father-and-son combo who won the Nobel Prize together). At the time of writing it is held by Richard Friend, a specialist in carbon semiconductors.

Notes

1 – The details of the Grace of the Senate of the University of Cambridge of 9 February 1871 are reproduced in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 350.

2 – Blore's letter to Maxwell telling him about the Cavendish Professorship is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 611.

3 – Maxwell's reply to Blore about the Cavendish Professorship is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 611.

4 – Lord Rayleigh's letter to Maxwell hoping that Maxwell will take the new professorship was written from Cambridge on 14 February 1871 and is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 349.

5 – The initial quote from Maxwell's inaugural Cambridge lecture is taken from William Davidson Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1890), p. 250.

6 – The later quote from Maxwell's inaugural Cambridge lecture is taken from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 356.

7 – George Stokes' comment about the difficulty of getting a house in Cambridge is reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 615.

8 – Maxwell's comments on John Hunter in a letter to Peter Tait are recorded in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), p. 836.

9 – George Bettany's complaint of the difficulty imposed by the Mathematics Tripos on Natural Science at Cambridge is from George Bettany, 'Practical Science at Cambridge', *Nature*, 11 (1874): 132–3.

10 – Isaac Todhunter's 1873 dismissal of the need for students to see experiments is from Isaac Todhunter, *The Conflict of Studies* (Cambridge: Cambridge University Press, 2014), p. 17.

11 – The attempt by Corpus Christi College to sue the university because the Cavendish Laboratory blocked its light is described in R. Wills and J.W. Clerk, *The Architectural History of the University of Cambridge*, Vol. 3 (Cambridge: Cambridge University Press, 1886), p. 183.

12 – Maxwell's comment about moving around like a cuckoo without a fixed location to lecture is from William Davidson Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1890), p. 760.

13 – Maxwell's letter to Katherine written in London and dated 20 March 1871 about the targets of the laboratory is reproduced in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 381.

14 – Maxwell’s list of requirements for the Cavendish Laboratory is from a letter to William Thomson written at the Athenaeum Club on 21 March 1871 and reproduced in Peter Harman (ed.), *The Scientific Letters and Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1995), pp. 624–8.

15 – Trotter’s letter to Maxwell on the benefits of giving researchers their own space is quoted in Isobel Falconer’s chapter on ‘Cambridge and the Building of the Cavendish Laboratory’ in Raymond Flood, Mark McCartney and Andrew Whitaker (eds.), *James Clerk Maxwell: Perspectives on his Life and Work* (Oxford: Oxford University Press, 2014), p. 84.

16 – The *Nature* editorial comparing Cambridge unfavourably with continental universities was in ‘A Voice from Cambridge’, *Nature*, Vol. 8 (1873): 21.

17 – Maxwell’s undated poem ‘Lectures to Women on Physical Science I’ is quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 631.

18 – Garnett’s observation on Maxwell’s reluctant acceptance of women on a Long Vacation course is quoted in Isobel Falconer’s chapter on ‘Cambridge and the Building of the Cavendish Laboratory’ in Raymond Flood, Mark McCartney and Andrew Whitaker (eds.), *James Clerk Maxwell: Perspectives on his Life and Work* (Oxford: Oxford University Press, 2014), p. 86.

19 (footnote) – The *Telegraph’s* reaction to a woman coming top in the Mathematics Tripos is quoted in Caroline Series, ‘And what became of the women?’, *Mathematical Spectrum*, Vol. 30 (1997/8), pp. 49–52.

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[*] The idea that physics would become largely about adding another decimal place was very clearly in the mind of the physicist Phillip von Jolly, when in 1874 he encouraged the student Max Planck (who went on to win the first Nobel Prize in Physics) to study music rather than physics. This was because von Jolly believed that physics was almost complete, and with a couple of small problems cleared up, all that remained was better measurement. In the early twentieth century Planck and Einstein would shatter this idea with the culmination of those small problems: relativity and quantum theory.

[†] This was Maxwell in the entertainingly flippant mode he often used in letters to friends. Hunter had researched the absorption of vapours.

[‡] Maxwell clearly had a cruel streak when it came to demons.

[§] And, yes, it still was just men.

[¶] No relation to William Thomson.

[||] Cambridge would eventually bite the bullet on this and move the main physics site to the New Cavendish, located on wide open spaces to the west of Cambridge at the start of the 1970s. Some physics work continued in Maxwell’s old Cavendish building for a number of years, but at the time of writing, part of the Cavendish is scheduled for demolition to provide better access to other buildings. There is a hope that the core of Maxwell’s structure can be retained and opened as a visitor centre.

[**] Ditto.

[††] Maxwell’s sense of humour to the fore. He was not seriously suggesting employing the university’s crew for the boat race as the motive power for experiments.

[‡‡] It is interesting that just twelve years after the publication of Darwin’s *Origin of Species* (a book some would even today regard as distinctly demonic), Trotter was comfortable using the concept of natural selection as a generally understood shorthand.

[§§] A very barbed comment, bearing in mind the antipathy that was still felt for France in the UK at the time.

[¶¶] The *Daily Telegraph* noted: ‘And now the last trench has been carried by Amazonian assault, and the whole citadel of learning lies open and defenceless before the victorious students of Newnham and Girton. There is no longer any field of learning in which the lady student does not excel.’

[||||] The second was definitely in 1874, but the first was undated.

[***] The name given to the summer vacation at Cambridge. Teaching during the Long Vacation, particularly between second and third years of the Natural Sciences Tripos, still takes place.

[†††] He of the ‘God runs electromagnetics on Monday …’ quote – see page 201.

Demonic Interlude VII

In which the demon's memory is challenged

JCM absolutely transformed physics at Cambridge – and we can see this as the last step of the huge changes he made to physics and your everyday world as a whole. Before his time, physics was in many ways an amateur discipline and (as far as experimental physics went) one where mathematics had a limited role. Post-Maxwell, to be a professional physicist was a significant position – people don't say 'It's not rocket science' for nothing – and maths was crucial to its development.

Of course, it's impossible to say for certain how things would be in your world without JCM. Most importantly, of course, you wouldn't have me. But at the very least, work on electricity and magnetism would have been put back significantly, and JCM's work would not only form the backbone of the technological developments of the twentieth century but would also be necessary to introduce both relativity and quantum theory, the two pillars of modern physics.

Without the Maxwell touch, Einstein would have been left foundering and quantum physics would never have been developed, dependent as it was on wholly mathematical models. Despite all this, our man, James Clerk Maxwell, for some reason barely crosses the awareness of the general public. It's remarkable that 78 per cent of readers of this book had never heard of Maxwell before coming across it.[*]

Forgetting is never easy

So, JCM's position in history is solidly established. But what about me?

You may remember that we left my status somewhat battered by Leo Szilard's suggestion that there would have to be a use of energy, increasing entropy, for me to make a measurement and store the information in my brain. However, as information theory became better developed, it was discovered that it is perfectly possible to store data and make computations without the expenditure of energy. With a bound, it seemed, I was free – I could do the job my creator had designed me for without using energy and pushing up entropy levels.

Unfortunately, there was a sting in the tail of this route to freedom. The physicist behind the breakthrough, Rolf Landauer, made a second, distinctly counter-intuitive discovery. While it need not take energy to store information or to make calculations, erasing information *does* result in exactly the amount of energy Szilard had calculated being put into the system, countering the apparent problem of the reduced entropy. Bear in mind, if you can put energy into the system it is perfectly possible to reduce entropy – to produce the low-entropy arrangement of letters in this book, for example, as opposed to a scrambled-up set of letters, the author had to exert energy to make it happen.[†] Similarly, refrigerators manage to reduce entropy, shifting heat from a warmer to a colder place because energy is pumped into them from their power source.

So, it seemed that Szilard wasn't entirely wrong, but he assigned the energy requirement to the wrong part of the process, to acts of measurement and storing data away, rather than forgetting. The actual justification for the erasure of information requiring energy is complex, but it depends on the concept of reversibility. If a process can be run forwards or backwards without distinction it is known as a reversible process and does not increase entropy. But if it is not possible to reverse it without energy consequences, it will increase entropy.

If we consider the parallel of what is supposed to be going on in my demonic brain as a simple sum such as 2 + 5 = 7, given the sum, the process is reversible. If I know what operation is involved, given any two numbers from it, I can recreate the rest. But if I erase the two values that make up the left-hand side of the sum and am left with only the 7, I can't get back to the 2 and the 5. It's not the action of computing the sum that makes it irreversible and hence increases entropy, it's the process of forgetting what the sum actually was.

What has all this information theory stuff got to do with me and the molecules? Followers of Landauer argued that however big my memory was, I would eventually run out of storage as a result of having to deal with so many billions of gas molecules, and so would have to erase what was stored in order to continue with the process – as a result, I would end up countering the benefit I had produced.

In 2017 researchers published a paper entitled 'Observing a quantum Maxwell demon at work', which they claimed gave them insight into my mind. Their 'demon' was a decidedly inferior object in the form of a superconducting cavity which held microwaves. It interacted with a small superconducting circuit which could give off or absorb a photon of light. The demon controlled the system, ensuring light could only be drained from the system, not absorbed, transferring the energy in one direction.

The team allegedly probed the demon's memory using something called quantum tomography that allowed them to use multiple runs of the system to build up a picture of what was happening in the memory – and they apparently showed that, in order to work, the demon had to keep information about the state of the system, seeming to prove the assertion that I could only bend the second law if I didn't forget things.

For many, the whole business of the erasure of memory was the end of my story. However, it's entirely possible that they really hadn't thought things through particularly well, as we shall discover. But we should first return to JCM at Cambridge, as he continues in his new role as Cavendish Professor.

Notes

1 – The paper apparently probing a quantum demon's mind is Nathanaël Cottet, Sébastien Jezouin, Landry Bretheau, Philippe Campagne-Ibarcq, Quentin Ficheux, Janet Anders, Alexia Auffèves, Rémi Azouit, Pierre Rouchon and Benjamin Huard, 'Observing a quantum Maxwell demon at work', *Proceedings of the National Academy of Sciences*, 114(29) (2017), pp. 7561–64.

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[*] I can say this because I am a demon and so can make up statistics. In reality, I have no idea how many readers had never heard of him, but Maxwell has always scored badly for name recognition compared with the likes of Newton, Faraday and Einstein, or even Schrödinger and Heisenberg (though most younger people probably think the latter is just a character in *Breaking Bad*).

[†] Apart from these demonic interludes, which he allowed me to put together, so he could sit back and do nothing.

Chapter 9

The last work

Maxwell had a belief in the openness of science, and as a result he probably did not provide enough direction and guidance to build effective staffing for the Cavendish during his time, a failing that would later have to be corrected. His approach was a result both of limitations on his time and a philosophy that was strongly geared to giving researchers their heads. He was quoted by Manchester-based physicist Arthur Schuster in Schuster's contribution to a 1910 history of the Cavendish Laboratory as saying: 'I never try to dissuade a man from trying an experiment. If he does not find what he wants, he may find out something else.'

Books and the power of light

Instead, a lot of Maxwell's time during his Cambridge years was dedicated to his writing. It was while at Cambridge that he published both his *Theory of Heat* and *Treatise on Electricity and Magnetism,* each of which attracted a far wider readership than we would now expect for a technical science book. The *Theory* was reviewed so widely that even *The Ironmonger* felt the need to comment, saying that 'the language throughout is simple and the conclusions striking'. To be fair, Maxwell's subtitle (which now seems somewhat condescending) was 'Adapted for the use of artisans and students in public and science schools'. The *Treatise* was arguably Maxwell's written masterpiece and was still in use as a textbook well into the twentieth century.

For the first year or so, the move to Cambridge and getting work started on the Cavendish Laboratory got in the way of Maxwell finishing his 1,000-page masterpiece on electromagnetism – but the *Treatise* was finally brought out in 1873, at the same time as parts of the new building were starting to be usable.

As always, Maxwell was not happy to leave his work as it was, but insisted on pulling at the threads of new ideas, looking for gaps to fill and inaccuracies to iron out. As he did so, he realised a strange implication of his predictions on the nature of electromagnetic waves. Not only did these waves correspond so clearly to light, they appeared to be capable of something that no one suspected light could do – electromagnetic waves should be able to apply pressure to matter. If his theory was correct, an insubstantial beam of light should be able to push a solid object.

This seems a crazy concept. Almost all of our experience of light suggests that its effects on physical objects would not be able to move them – yet Maxwell calculated that there should be a small force generated by the interaction between electromagnetic waves and the matter they illuminated. There was one physical phenomenon that did suggest such an effect could be occurring. As we have seen (page 173), Maxwell had already given some consideration to the way that a comet's tail always points away from the Sun. The idea of pressure from light was a possible explanation for this. Maxwell gave this hypothesis a theoretical backing by showing that the energy of absorbed light should result in momentum being added to the body absorbing it.

The reason we don't see this happening as a rule, Maxwell suggested, was because the effect was so small. He calculated that the Sun, the most powerful light source in our vicinity, would only produce the equivalent pressure of 7 grams (0.015 pounds) across a whole hectare (2.47 acres) of area. Maxwell would never see an experimental demonstration of the effect that he had predicted, but 25 years after his theory was published, the Russian physicist Pyotr Lebedev demonstrated this 'radiation pressure' for the first time.

The concept of radiation pressure is not just a partial explanation for comets' tails (in practice the effect is primarily due to the 'solar wind', a flow of particles from the Sun). It has also been suggested as a possible way of powering spaceships by light, using immense sails to catch the light from the Sun or from a battery of lasers. But most important of all, it is an essential phenomenon to be able to understand how stars operate. Without it, the Sun would not function. The matter in stars is subject to immense inward pressure from gravity – it is the radiation pressure of the vast numbers of photons of light produced inside the star that is the first level of defence against gravity's attempts to make the whole thing collapse.

The *Treatise* was not just Maxwell's masterpiece, it was his last significant work. He published a short piece in *Nature,* improving Ludwig Boltzmann's treatment of the kinetic theory of gases (itself derived from Maxwell's work, but taking it sufficiently further that Boltzmann and Maxwell are fairly considered joint initiators of the theory). And he continued to work on many of his lesser pet projects, from colour vision to the theory of optical instruments, where he expanded the tools available for the theoretical description of multi-lensed instruments – a practical study, though not as distinctively original as his main topics of work.

Most of his effort over the next couple of years, however, was dedicated to building up and running the Cavendish Laboratory. What spare time he had was given to a job that many have since thought was a matter of shouldering an obligation – but in reality, he could well have been following a topic of great personal interest.

The Cavendish papers

As we have seen, Henry Cavendish, the ancestor of the Duke of Devonshire who funded the Cavendish Laboratory, was an important scientist in his own right. From about 1873 onwards, Maxwell dedicated a considerable amount of his time to editing the papers of Cavendish. This could, indeed, have been a way of thanking the present Duke for the funding – but the money for the laboratory was already in place and it seems more likely that Maxwell had a genuine interest in untangling the details of Henry Cavendish's work. Arguably, this could have come from the same kind of drive that inspires people to look into their ancestry – this was, in effect, establishing the ancestry of his laboratory – and also because Henry Cavendish had done a considerable amount of original work that was not widely known, and that Maxwell felt should be available to other physicists.

Cavendish is probably best remembered for measuring the density of the Earth,[*] an experiment that would enable the first calculation of Newton's gravitational constant G, and for discovering hydrogen. But from Maxwell's viewpoint, Cavendish's most interesting work was in electricity, a field that Cavendish studied for ten years from 1771. Most notably, Cavendish demonstrated the inverse square law of electrical repulsion well before the French physicist Charles-Augustin de Coulomb did. Yet it was Coulomb who was acknowledged as the discoverer of the law, as Cavendish never published this part of his work.

It is not uncommon to see suggestions that Maxwell wasted much of the little time he had left to him on the Cavendish papers. However, leaving aside the benefits of hindsight – he had no idea that he hadn't long to live – there is no evidence that Maxwell was pressured into doing the work, either by the university or by the Duke of Devonshire. Quite the reverse: Maxwell appears to have first shown an interest in getting hold of Cavendish's papers two years *before* his involvement at Cambridge. Not only did he edit Cavendish's output, pulled together from reluctant owners with the help of the Duke, he also recreated some of Cavendish's experiments, using period instruments which had come into his possession from the collection of William Hyde Wollaston.

Some of Cavendish's results added extra information to work on electromagnetism. Maxwell commented: 'if these experiments had been published in the author's life time the science of electrical measurement would have been developed much earlier.' Other parts of Cavendish's papers simply seemed to appeal to Maxwell's personality and sense of humour.[†] He was delighted with the way that Cavendish had used the pain reaction of his own body as a 'meter' to test the strength of electrostatic energy. Maxwell recreated this approach, using anyone he could persuade to volunteer to try out the technique.

Arthur Schuster remembered:

> … a young American astronomer expressing in severe terms his disappointment that, after travelling on purpose to Cambridge to make Maxwell's acquaintance and to get some hints on astronomical subjects, the latter would only talk about Cavendish, and almost compelled him to take his coat off, plunge his hands into basins of water and submit himself to the sensation of a series of electrical shocks.

Maxwell's edition of Cavendish's papers was published in October 1879, shortly before his death.

Passing fancies

Typically, though Maxwell spent the majority of his time on his better-known fields of interest, he could not help being drawn briefly into any passing curiosity that took his fancy. For example, in 1874 he wrote to his old friend Lewis Campbell about what would now be called genetics, considerably before the concept of the gene was widely known.[‡] Admittedly, Maxwell did so to dismiss the concept – but based on what he thought was the case, his argument made sense. He wrote:

> If atoms are finite in number, each of them being of a certain weight, then it becomes impossible that the germ from which a man is developed [i.e. the cell] should contain … gemmules[§] of everything which the man is to inherit, and by which he is differentiated from other animals and men, – his father's temper, his mother's memory, his grandfather's way of blowing his nose, his arboreal ancestor's arrangement of hairs on his arms … if we are sure that there are not more than a few million molecules in [the cell], each molecule being composed of component molecules, identical with those of carbon, oxygen, nitrogen, hydrogen etc., there is no room left for the sort of structure which is required for pangenesis on purely physical principles.

Maxwell proved to be wrong, by attributing too much to genetics, underestimating the number of molecules available, and in the scale of information that can be stored in a germ cell – but the fact that he was discussing this concept long before the significance of DNA and its genes was realised shows the range of his interests and thoughts.

One of the most entertaining of Maxwell's diversions was the Crookes radiometer, a puzzling device that was introduced to the world in 1874. William Crookes was an English scientist a year younger than Maxwell, who would go on to do important work on electrical effects in vacuum tubes, the precursors of thermionic valves, which were the first electronic devices.

Crookes' radiometer looked a little like a light bulb. It was a sealed glass chamber with the air mostly pumped out, but rather than having a filament inside, it had four paddles suspended from a central spindle so that they could freely rotate. Each paddle was white or silver on one side and black on the other – and when exposed to light, the paddles would rotate at high speed.[¶] At first sight this might have seemed to be a vindication of Maxwell's idea of radiation pressure – but the radiometer spins in the wrong direction for this (and anyway, Maxwell was aware that the amount of pressure on the paddles from radiation would not be sufficient to turn them).

If the spinning paddles had been pushed by radiation pressure you would expect that the white/silver sides would move away from the light, as they would be reflecting far more of the light than would the black sides. In fact, however, it's the black sides that move away from the light, which caused confusion and delight in equal measures among the scientific intelligentsia.

Maxwell would come to the rescue, aided by some practical information from his friend Peter Tait. With his colleague James Dewar, the inventor of the vacuum flask and an expert on low-pressure work, Tait had discovered that the working of the radiometer was dependent on the amount of air that was left in the bulb. No experimental vacuum was perfect – there would always be some gas molecules present. With too much air or with too little, the radiometer would not work.

Realising that the mechanism must depend on one of his other favourite topics, the kinetic theory of gases, Maxwell seems to have put himself in the frame of mind of one of his demons, able to see the gas molecules in action near to the paddles. When the light was shone onto the paddles, the black sides would absorb more of the light and would heat up. This, he thought, would speed up gas molecules that came into contact with the paddles, producing convection currents around the sides of the paddles, which would effectively suck the paddles round.

With many of his theories, Maxwell wasn't quite there in his first attempt – this turned out to be the case with the radiometer, where his calculations let him down a little. The actual solution turned out, if anything, to be simpler. Gas molecules coming into contact with a warmer black paddle surface would gain a little more energy than those that hit a cooler white side. This meant that, on average, the black sides were being bombarded with more momentum than the white and started to move away from the pressure.

Although Maxwell's convection currents turned out not to be the driving force behind the radiometer, his effort was by no means wasted. In writing up his work for the Royal Society he generalised his mathematics to provide an equation for the behaviour of gases in such rarefied conditions which would prove to be valuable in studies of the upper atmosphere.

A sudden end

The paper inspired by the radiometer would be Maxwell's last contribution to science. In early 1877, he began to have problems with his digestive system. Maxwell suffered frequent heartburn and found swallowing an increasing problem. The discomfort got worse over two years before he consulted his doctor, who took him off meat and replaced it with a milk-based diet.

In the summer of 1879, James Clerk Maxwell was diagnosed with abdominal cancer. He died in Cambridge on 5 November 1879, just 48 years old – the same age as his mother at her death.

Maxwell's funeral was effectively split in two. The first part of the burial service took place in the Trinity College chapel in Cambridge, attended by many of his academic colleagues and friends. His coffin was then taken home to Glenlair, with the closing part of the funeral service held at Parton church, before his burial in the churchyard there.

Notes

1 – Arthur Schuster's quote from Maxwell on never dissuading a man from trying an experiment is from Arthur Schuster, *A History of the Cavendish Laboratory* (London: Longmans, Green and Co., 1910), p. 39.

2 – The review from *The Ironmonger* on Maxwell's *Theory of Heat* is reproduced in Isobel Falconer's chapter on 'Cambridge and the Building of the Cavendish Laboratory' in Raymond Flood, Mark McCartney and Andrew Whitaker (eds.), *James Clerk Maxwell: Perspectives on his Life and Work* (Oxford: Oxford University Press, 2014), p. 76.

3 – Maxwell's comment that if Cavendish's papers had been published earlier, electrical measurement would have been developed much earlier is in William Davidson Niven (ed.), *The Scientific Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1890), p. 539.

4 (footnote) – Maxwell's description of himself as dp/dt comes from the equation dp/dt = JCM which shows the change of pressure as temperature changes, with J being Joule's equivalent, C Carnot's function and M the rate at which heat must be supplied per unit increase of volume, the temperature being constant.

5 – Arthur Schuster's recollection about an American complaining of being subject to electrical shocks by Maxwell is from Arthur Schuster, *A History of the Cavendish Laboratory* (London: Longmans, Green and Co., 1910), p. 33.

6 – Maxwell's comments on units of inheritance are quoted in Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 390.

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[*] He is also remembered for being extremely eccentric. Cavendish was so shy that he did not like to speak to more than one person at a time and would only communicate with

female servants by notes. Complex arrangements ensured his meals could be served with minimal contact with staff.

† It's easy to think of Maxwell, from his dour photographic portraits, as a typical miserable Victorian, but all his life he displayed an impish (appropriately enough) sense of humour. This often came through, as we have seen, in his letters, which could be distinctly whimsical. For example, he tended to refer to himself as dp/dt – since an equation in his friend Peter Tait's book read dp/dt=JCM, Maxwell's initials. (See notes for detail of the equation.)

‡ The word 'gene' was not introduced until 1905. The concept behind the gene was in Gregor Mendel's work suggesting that a unit of inheritance did exist, which was published in 1866, but it was not widely known until after Maxwell's death.

§ Darwin's term for a unit of inheritance.

¶ You can see a Crookes radiometer in action at the *Universe Inside You* website page: http://www.universeinsideyou.com/experiment4.html

Demonic Interlude VIII

In which the demon lives on to fight another day

With the sad news of James Clerk Maxwell's demise, it would be easy to consider us both finished. You may recall that many thought I could no longer do my job as a result of the suggestion that it would take energy to erase information, and so, in the overall system including me, entropy would not be reduced. There was one attempt, with a complex argument, to provide a way in which it would be possible to make the erasure process reversible, though many argued that this was cheating, since it required dumping information into an external store – which surely itself was also finite.

The reality of loopholes

Even so, I was thought to be doomed. However, there is a loophole which remains to this day. Although it's true that eventually I would have to wipe some memory, it is also true that in any particular experiment I could still perform my task. There may be many billions of molecules in an experiment, but I can also have an equivalent amount of storage and perform my task without any erasure. Admittedly I wouldn't have enough memory space to run the experiment for ever, but I would be able to reduce entropy to a considerable degree before I ran out of storage – there is no need for me to deal with every single molecule available over all time.

Those who wish me disposed of suggest that this is not an acceptable argument because of the way thermodynamics is practised. Generally, this involves cyclic processes where the components are returned to their initial state, and the argument is that I should be left in the same state after working on a molecule as I was before it – which wouldn't allow me a memory. But that's something of a silly argument, as without any memory I couldn't do my job in the first place – and the whole process is clearly not cyclical when molecules are being irreversibly moved from one side of the box to the other. It seems an argument more from dogma than from physics.

More to the point, other physicists have come up with a concept they call blending which achieves the irreversibility of erasure without any influence over the entropy of the system. To quote one such example from Meir Hemmo and Orly Shenker:

> In particular, the principles of mechanics entail no specific relation between the pre-erasure and post-erasure entropy of the universe. In any case, our analysis of erasure demonstrates that, contrary to the conventional wisdom, classical mechanics does not entail that an erasure is necessarily dissipative [i.e. increasing entropy].

That being the case, I hope you are clear that the challenge JCM set so long ago is, to a degree, still there. I am still a thorn in the side of the second law – almost inevitably, given its statistical nature. Despite the theoretical objections to my existence (rather demonist, if you ask me), a number of recent experiments have shown that demonic action is possible as long as you work on a small enough scale.

In 2016 for example, at the University of Oxford, a team made use of two pulses of light instead of the two sides of my original box. Rather than employ a true demon (apparently, despite the suggestions of Philip Pullman, we are of limited availability in Oxford labs), they made a measurement on two pulses of light and depending on which was stronger, took one pulse in one direction and the other in another. The difference between the voltage produced by photodiodes receiving the two pulses charged up a capacitor. Because the more energetic pulses always go the same way, the result is to be able to produce work from a demon-style interaction.

Closer to the original because it has a thermodynamic element, also in 2016 a Brazilian physicist and his team performed an experiment that seemed to contain its own tiny demon. They managed to produce a situation where the second law was more clearly spontaneously broken, if on a small scale. This was something that must have struck joy into the heart of those who peddle ‘free energy’ devices. Physicists dismiss perpetual motion machines and free energy devices out of hand. Some consider this a lack of open-mindedness, but in reality, it’s just that the physicists understand the second law of thermodynamics.

In the Brazilian experiment, heat moves from a colder to a hotter place. As we’ve seen, there’s nothing odd about heat moving from a colder to a hotter body: it's what a fridge does, after all. But this can only be the case if energy is supplied to make it happen – this is what the 'closed system' bit of the definition of the second law precludes. What is interesting in the described experiment is that heat was transferred spontaneously from 'colder' to 'hotter' (I'll come back to those inverted commas soon), which is what you need for perpetual motion and free energy.

Physicist Roberto Serra of the Federal University of ABC in Santo André, Brazil and the University of York, and his colleagues, got molecules of chloroform – a simple organic compound where a carbon atom has one hydrogen and three chlorine atoms attached – into a special state. The hydrogen atom and the carbon atom in a molecule had one of their properties – spin[*] – correlated, giving them a kind of linkage. The hydrogen atom was in a higher energy state than the carbon, making the hydrogen technically hotter than the carbon (hence the inverted commas above). And without outside help, as the correlation decayed, heat was transferred from the carbon to the hydrogen. From the colder to the hotter atom.

To understand why this happened requires the alternative definition of the second law, the one involving entropy. As we've seen, entropy is measured by the number of different ways the components of a system can be organised. The more ways, the higher the entropy. In the case of the chloroform experiment, entropy decreases because there are more ways to arrange the quantum states[†] when they are correlated than when the correlation goes away – it's a bit like there being more different ways to throw a six with two dice together than there are with either of two dice individually.[‡] However, free energy enthusiasts don't need to get too excited. Although there does appear to have been a spontaneous reduction in entropy, getting the molecules into the right state to start with would have taken far more energy than could be extracted. This is never going to be a free source of energy.

Dr Serra's chloroform molecules have none of the sophistication of a true demon at work – but they are an actual physical manifestation of that most enduring of laws being, at the very least, cheekily tweaked. Whether or not *my* challenge remains, one thing is certain. Our man, James Clerk Maxwell, has an impressive legacy and I'm proud to be associated with it.

Notes

1 – The assertion that the erasure of information need not result in the increase of entropy comes from Meir Hemmo and Orly Shenker, *Maxwell's Demon* (Oxford: Oxford Handbooks Online, 2016), accessed at: http://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780199935314.001.0001/oxfordhb-9780199935314-e-63

2 – The Oxford University paper describing a photonic demon is Mihai Vidrighin, et al., 'Photonic Maxwell's Demon', *Physical Review Letters*, 116 (2016), p. 050401.

3 – The chloroform-based quantum demon is described in Patrice Camati, et al., 'Experimental rectification of entropy production by Maxwell's demon in a quantum system', *Physical Review Letters*, V. 117 (2016), p. 240502.

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[*] Quantum spin is one of the standard properties of a quantum particle. It was called spin as it loosely corresponds to the familiar rotation of an object, but it does not involve actual spinning around: quantum spin has values of multiples of a half, and can only be either up or down in the direction of measurement.

[†] The quantum state of a particle (or system) is the collection of the values of its properties such as charge, spin, etc.

[‡] With two dice individually, you can only get a six if six comes up on one of the dice. But with two dice together you can get a six with 1+5, 2+4 and 3+3.

Chapter 10

The legacy

If you were to ask a scientist around the end of the nineteenth century who – of that century's big names – scientists in the future would regard as the leading British physicist of the era, he would undoubtedly have said Lord Kelvin. Maxwell's old friend William Thomson was feted in his day – a reality that was reflected in his elevation to the House of Lords, the first scientist ever to have received this honour.* Certainly, there is no doubt that Kelvin did essential work in thermodynamics, as well as working on many practical applications of science – his name appears on over 70 patents of the period, and as we have seen, he was a leading figure in the laying of the transatlantic cable.

It was Kelvin, not Maxwell, who ended up alongside Isaac Newton in Westminster Abbey, and Kelvin who has a scientific unit named after him. Not long after Kelvin died in 1907, statues of him would be erected in both his birthplace of Belfast and in the city where he did the majority of his work, Glasgow. By contrast, Maxwell was buried in a little country churchyard and there would not be a statue of him put up in his native Scotland for over 100 years after his death.

By the first half of the twentieth century, though, the picture was transformed. While Kelvin's achievements have not been belittled, they now seem a lot less significant in the grand scheme of things. By comparison, the appreciation of Maxwell's work on electromagnetism, his contribution to statistical mechanics, and his transformation of the way that theoretical physics was undertaken have made him far more of a hero to modern physicists. It's not for nothing that Einstein is reported as saying: 'There would be no modern physics without Maxwell's electromagnetic equations; I owe more to Maxwell than to anyone.'

Those who knew him best were aware from the outset that there was something special about James Clerk Maxwell. His friend since schooldays, Peter Tait, wrote of him in *Nature* at the end of a summary of

Maxwell's work, providing a eulogy that would stand up well today in its reference to the resistance to 'vain-babbling' and pseudo-science:

> I cannot adequately express in words the extent of the loss which his early death has inflicted not merely on his personal friends, on the University of Cambridge, on the whole scientific world, but also, and most especially, on the cause of common sense, of true science, and of religion itself, in these days of much vain-babbling, pseudo-science, and materialism.

There was something very special about Maxwell's breadth of contribution. Charles Coulson, who in 1947 took on the same chair that Maxwell had held at King's College London, remarked: 'There is scarcely a single topic that he touched upon which he did not change almost beyond recognition.' This volume of output was matched by Maxwell's insight – his ability to develop models and mathematics to model reality when this approach was a novelty. In a booklet put together to celebrate the centenary of Maxwell's birth in 1931, the English physicist James Jeans gave striking testimony to this intuitive force when describing Maxwell's distribution for the velocities of gas molecules. Jeans wrote:

> Maxwell, by a train of argument which seems to bear no relation at all to molecules, or even to the dynamics of their movements, or to logic, or even to ordinary common sense, reached a formula which according to all precedents and all the rules of scientific philosophy, ought to have been hopelessly wrong. In actual fact, it was subsequently shown to be exactly right … it was this power of profound physical intuition, coupled with adequate, though not outstanding mathematical technique, that lay at the basis of Maxwell's greatness.

It's not uncommon when trying to give Maxwell his rightful place in the pantheon of physics to bracket him with Newton and Einstein (probably throwing in Faraday as well). And though there is no doubt that a considerable amount of Newton's work was concerned with physics, it's arguable that Newton was far less of a physicist than Maxwell.

It's interesting to compare the catalogues of Newton's and Maxwell's libraries. Newton left behind a remarkable[†] 2,100 books. Of these 109 were on physics and astronomy, 138 on alchemy, 126 on maths and 477 on theology.[‡] By comparison, over half Maxwell's books were on physics. Newton was arguably an applied mathematician (when he wasn't occupied as an alchemist, a theologian or working at the Mint). Maxwell, like Einstein, was undoubtedly a physicist.

Looking back from the twenty-first century, Maxwell comes across as unusually unstuffy for his day. Someone far from the stereotypical image of the humourless Victorian scientist. And we are now also in a position to appreciate just how much his work on electromagnetism would help launch a technological revolution.

Considering how fresh much of Maxwell's science was, we can see in some of his later writing and talks a very modern approach to scientific matters. In 1873, he gave a speech entitled 'Discourse on molecules' at the British Association's meeting in Bradford, a small part of which makes an ideal dip into Maxwell's own words.

> In the heavens we discover by their light, and by their light alone, stars so distant from each other that no material thing can have passed from one to the other;[§] and yet this light, which is to us the sole evidence of the existence of these distant worlds, tells us also that each of them is built up of molecules of the same kinds as those which we find on earth. A molecule of hydrogen, for example, whether in Sirius or in Arcturus, executes its vibrations in precisely the same time.
>
> Each molecule therefore through the universe bears impressed on it the stamp of a metric system[¶] as distinctly as does the metre of the Archives at Paris, or the double royal cubit in the temple of Karnak.
>
> No theory of evolution can be formed to account for the similarity of molecules, for evolution necessarily implies continuous change, and the molecule is incapable of growth or decay, of generation or destruction.
>
> None of the processes of Nature, since the time when Nature began, have produced the slightest difference in the properties of any molecule.

At this point, Maxwell deviates from modern science as he assumes that molecules have to have been made from something, given their identical nature, but that there was no process that could do so that 'we can call natural'. We now know there are perfectly natural processes for the interchange of matter and energy which can account for the creation of matter, but when Maxwell wrote, this science was still 23 years in the future, with Einstein's special theory of relativity. (And the special theory would not have come about without Maxwell's work.) Even so, until that point, and allowing for some change in language, we could have just as easily have been listening to a Brian Cox or Neil deGrasse Tyson expanding on the wonders of the universe as to a Victorian. Maxwell's vision was far removed from the semi-mystical meandering of earlier physics, a fault that stayed with it even when Newton and his followers had started to include some mathematics.

Throughout this book, a minor part of Maxwell's output – the demon – has played a significant role. I wanted the demon to have his say because he reflects so well Maxwell's ability to challenge the way that his colleagues thought about things, to use interesting new approaches to modelling, and to incorporate a touch of humour into what can be a very po-faced science. More than a great scientist, Maxwell seems to have been a remarkable man, someone with whom it must have been a pleasure to be a friend.

Maxwell and his demon deserve to be remembered as long as science has an impact on our lives.

Notes

1 – Einstein's claim to owe more to Maxwell than anyone is from Esther Salaman, 'A Talk with Einstein', *The Listener*, 8 September 1955, Vol. 54, pp. 370–71.

2 – Peter Tait's eulogy to Maxwell is from *Nature*, Vol. 21 (1880): 317–21.

3 – Charles Coulson's remark about Maxwell is from C. Dombe (ed.), *Clerk Maxwell and Modern Science: Six Commemorative Lectures* (London: Athlone Press, 1963), pp. 43–4.

4 – James Jeans' remarks about Maxwell's intuitive ability are from his entry, 'Clerk Maxwell's Method', in *James Clerk Maxwell: A Commemorative Volume 1831–1931* (Cambridge: Cambridge University Press, 1931), pp. 97–8.

5 – The quote from Maxwell's lecture on molecules is from Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (London: Macmillan, 1882), p. 358.

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[*] It's often said, incidentally, that Isaac Newton was the first person to be knighted for his contribution to science. I've even heard this claimed on that unequalled source of knowledge, the BBC's *Pointless* TV quiz programme. But in reality, Newton was knighted for doing a good job at the Royal Mint, where his enthusiasm for catching those who clipped the edges of coins to sell the metal (and for having them hanged, drawn and quartered) was legendary. A man after my own demonic heart, was Newton.

[†] Particularly for the period, when books were an expensive rarity.

[‡] Which Newton would have considered a science.

[§] Funnily, in saying this Maxwell was wrong, but for the right reason. At the time, the universe was thought to be much smaller than we now know it to be – but it was also considered so much younger that it was assumed there wasn't time for anything to get from one extreme of the universe to the other. The current Big Bang theory fixes this with a universe that expanded so quickly during the inflation phase that right at the beginning, the extremes of the observable universe could still have been in direct physical contact.

[¶] By 'metric system' Maxwell did not intend the modern usage of a system to base 10, but just a system of measurement.

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ABOUT THE AUTHOR

Brian Clegg is the author of many books, including most recently *The Graphene Revolution* (Icon, 2018) and *The Reality Frame* (Icon, 2017). His *Dice World* and *A Brief History of Infinity* were both longlisted for the Royal Society Prize for Science Books. Brian has written for numerous publications including *The Wall Street Journal, Nature, BBC Focus, Physics World, The Times, The Observer, Good Housekeeping* and *Playboy*. He is the editor of popularscience.co.uk and blogs at brianclegg.blogspot.com.

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