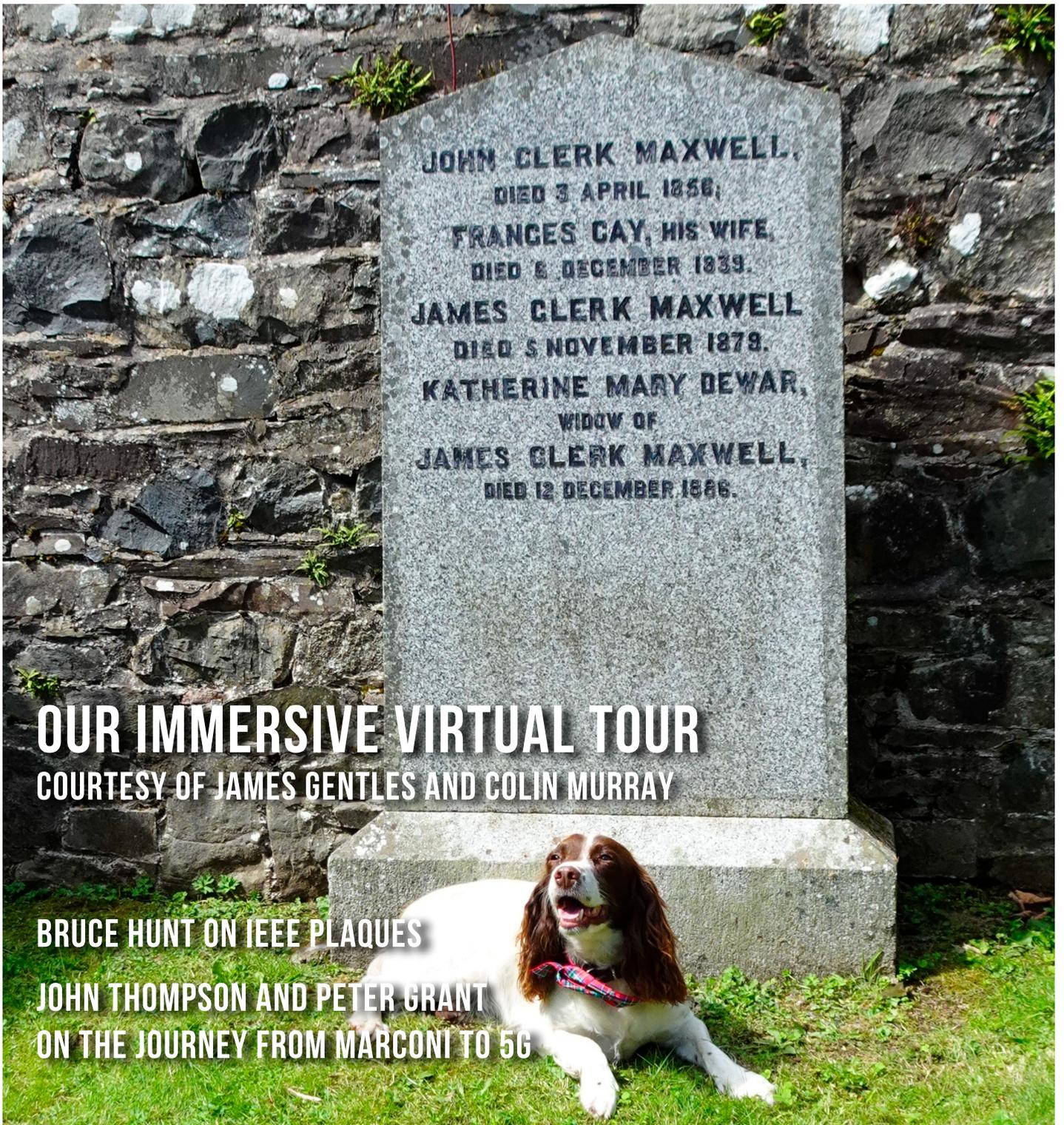


James Clerk Maxwell



The Maxwellian

THE JOURNAL OF THE JAMES CLERK MAXWELL FOUNDATION



OUR IMMERSIVE VIRTUAL TOUR
COURTESY OF JAMES GENTLES AND COLIN MURRAY

BRUCE HUNT ON IEEE PLAQUES
JOHN THOMPSON AND PETER GRANT
ON THE JOURNEY FROM MARCONI TO 5G

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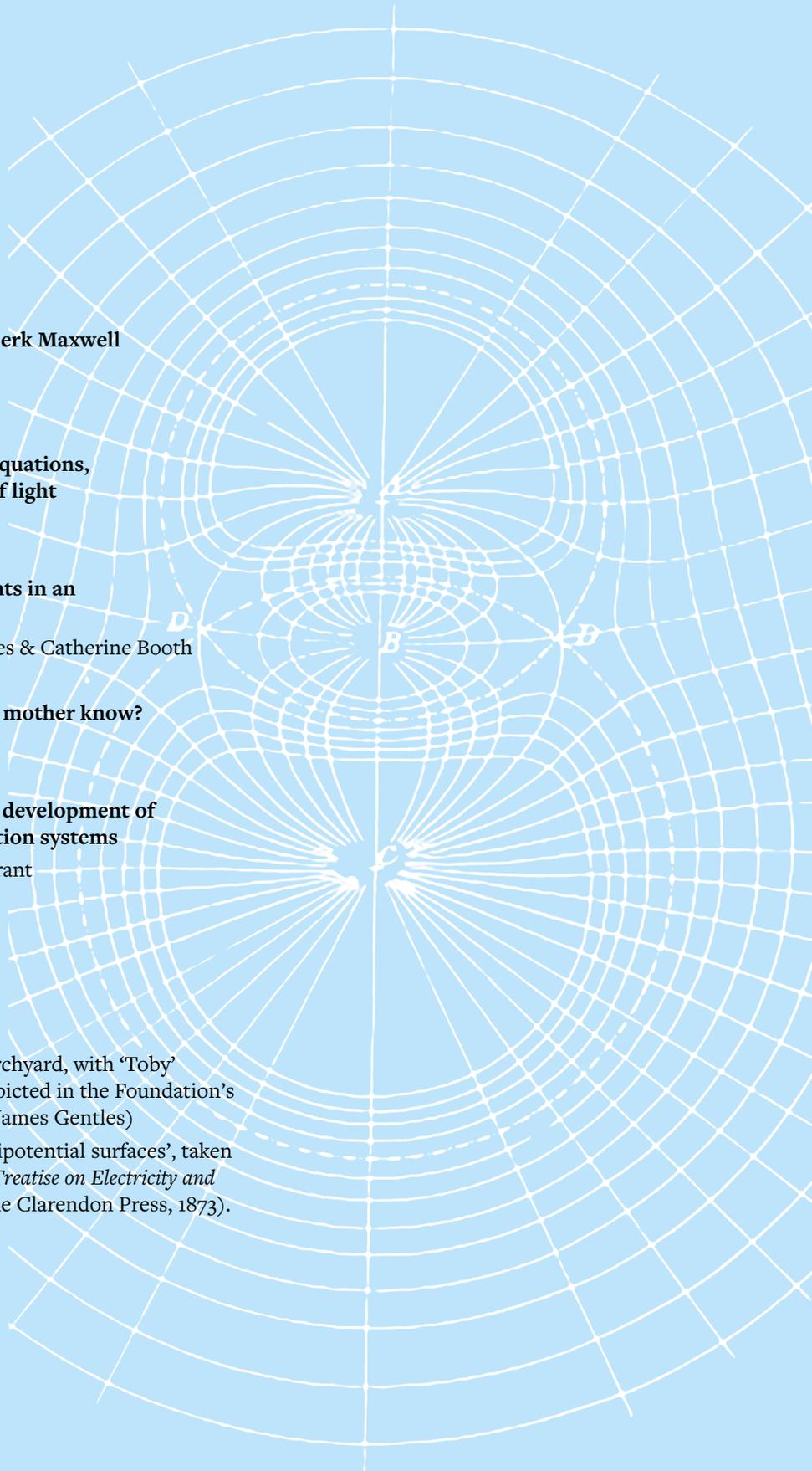
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EDITORIAL TEAM

- Dr Chris Pritchard
- Dr Catherine Dunn
Dr Howie Firth
Professor Peter Grant
Professor Martin Hendry



EDITORIAL

Chris Pritchard

Welcome to the third issue of *The Maxwellian*, a twice-yearly journal with a focus on the life and scientific legacy of the Scottish physicist, James Clerk Maxwell.

It was a pleasure to meet Bruce Hunt last summer when he visited 14 India St., the house in which Maxwell was born, and I was delighted when he agreed to write the lead article for this issue on the two IEEE plaques that can be found in the entrance hall. The plaques mark Maxwell's formulation of the electromagnetic field and his role in the establishment of the ohm as the standard of electrical resistance.

In a comprehensive overview, John Thompson and Peter Grant trace the development of mobile radio communication systems from Marconi to the present day. The first transatlantic transmission, made in 1901, is celebrated on another IEEE plaque, in Newfoundland rather than Edinburgh and this is included in their article. Of course, over the years there have been huge developments and some great pioneers. John and Peter detail the

contributions of the likes of Aleksandr Popov, Reginald Fessenden, Karl Ferdinand Braun, Edwin Armstrong, Richard Frenkiel, Thomas Haug and Philippe Depuis. But the efforts of these innovators would have been impossible without Maxwell and Hertz.

We at the Foundation are enormously grateful to James Gentles and Colin Murray who have almost completed the updating and upgrading of their Virtual Tour of Maxwell's haunts, and his homes in Edinburgh and Glenlair (to the east of Dumfries). They describe the project in this issue, and I am confident that you will be amazed by the scale and visual impact of their enterprise.

Finally, two less-formal articles. The first is a blog from Isobel Falconer on Maxwell's mother, Frances Cay. We hope that further blogs from Isobel will be included in later issues. The second, designed for our younger readers, is on images of Maxwell and other physicists and mathematicians on stamps and coins.

FOR OUR YOUNGER READERS

Noomi, Phil and James Clerk Maxwell

Chris Pritchard

Noomi and Phil, sister and brother, are not so much into the standard teen scene. Instead, they share a passion for mathematics and physics, and for collecting – Noomi saves coins while Phil is into stamps. Of course, all 'collecting hobbies' can be expensive, though it's amazing what can be discovered well within budget with some ferretting around. They used to check out market stalls and junk shops but now they're increasingly finding what they want online.

It started when Noomi discovered a triangular coin from Uganda featuring Pythagoras and his theorem.



It set her off looking for coins with tributes to other mathematicians and their ideas, and she soon found a coin from the former East Germany with a curve on it. Noomi's mathematics teacher was able to tell her about Carl Friedrich Gauss and the normal curve it depicted.

Meanwhile, Phil happened across Ernest Rutherford's quip that "all science is either physics or stamp collecting", and the controversy about whether he actually said it and, even if he did, whether he was implying that other sciences (chemistry and biology in particular) are inferior. Perhaps Phil didn't spot the irony in Rutherford's receiving the Nobel Prize for Chemistry in 1908, but he found plenty of it in his first stamp purchase.

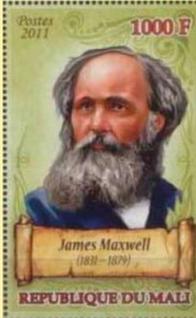


Anyway, since physics was Phil's favourite subject at school, acquiring the Rutherford stamp proved to be the first step towards a stamp collection featuring physicists. The next eight stamps he bought honoured Isaac Newton, James Watt, Michael Faraday, James Clerk Maxwell, Ludwig Boltzmann, Marie Curie, Albert Einstein and Enrico Fermi (shown overleaf).



The stamps from Nicaragua were amongst a set of ten celebrating mathematicians and physicists. This was the first time Phil had come across the ‘Ley de Maxwell’, i.e. Maxwell’s Law, one of the four equations which laid the groundwork for radio signals or, indeed, the ‘Ley de

Boltzmann’ (Ludwig Boltzmann’s entropy formula). It turned out that, years later, after leaving university, Phil would specialise in physical research arising from Maxwell’s ground-breaking electromagnetism theory, and so it’s wholly appropriate that he also collected Maxwell stamps:

<p>Mexico, 1967 80 Centavos stamp featuring Hertz, Maxwell and telecommunication</p> 	<p>San Marino, 1991 750 Lira stamp marking radio’s centenary</p> 	<p>Mali, 2011 1000 CFA Francs stamp, perhaps to mark 180 since Maxwell’s birth</p> 		
<p>Moldova, 2016 1.75 Leu stamp to celebrate 185 years since Maxwell’s birth</p> 	<p>Celebrating the International Year of Light and Light-based Technology, 2015</p> <table border="0"> <tr> <td data-bbox="564 1473 1023 1874"> <p>Moldova 1.75 Leu stamp (Maxwell’s equations)</p>  </td> <td data-bbox="1023 1473 1484 1874"> <p>Maldives 20 Rufiyaa stamp</p>  </td> </tr> </table>		<p>Moldova 1.75 Leu stamp (Maxwell’s equations)</p> 	<p>Maldives 20 Rufiyaa stamp</p> 
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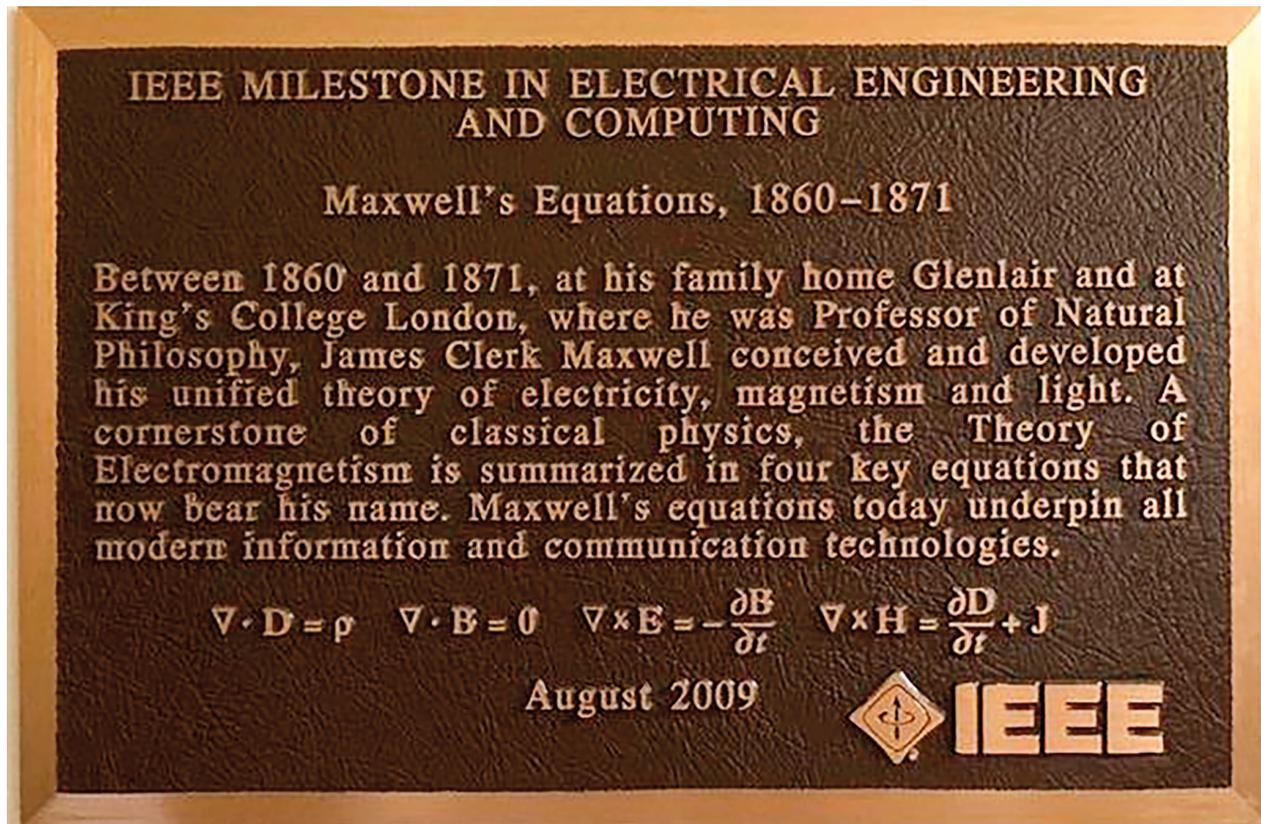
To access other stamps featuring physicists, go to <https://phys.bspu.by/static/hist/physstamp/physstamps.html>; to learn more about James Clerk Maxwell, you’re already in the right place!

TWO PLAQUES: MAXWELL'S EQUATIONS, THE OHM, AND THE SPEED OF LIGHT

Bruce J. Hunt

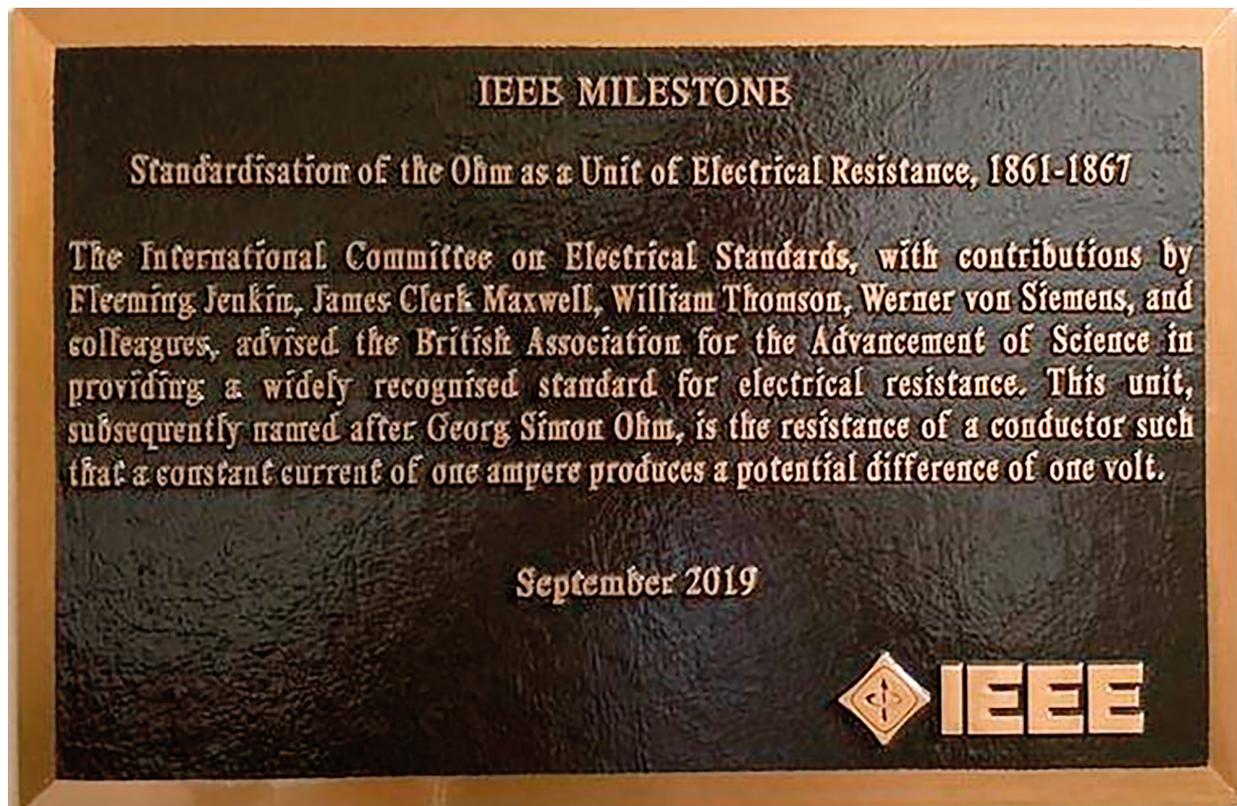
Two plaques erected by the Institute of Electrical and Electronic Engineers adorn the entry hall of Maxwell's birthplace at 14 India Street in Edinburgh, the home of the James Clerk Maxwell Foundation. The first, placed in 2009, commemorates Maxwell's formulation of the laws of the electromagnetic field, as expressed in the iconic set of four "Maxwell's equations." The second (next page), dating from 2019, recognizes Maxwell's role in establishing the ohm as the standard of electrical resistance. Apart from the fact that they both involve electricity and both

cite an overlapping period in the 1860s, the achievements celebrated by the two plaques might appear to have little connection. Certainly, ohms do not show up in Maxwell's equations, and the intricacies of his field theory would seem to be far removed from a humble resistance coil. But when we look more closely, we find that Maxwell's work on the ohm and his theory of the electromagnetic field were closely intertwined. They were connected, oddly enough, by the speed of light.



Maxwell first took up electromagnetic theory in the 1850s, just after completing his degree at Cambridge. He made a close study of Michael Faraday's *Electrical Researches* and, guided in part by William Thomson (later Lord Kelvin), began to cast Faraday's ideas about fields and lines of force into mathematical form. Building on Faraday's discovery that a magnetic field can rotate the plane of polarization of a beam of light, and on Thomson's proof that this implied that there must be spinning motion of some kind in the medium that carries the waves of light, Maxwell devised a model that depicted the ether as an array of tiny vortices separated by "idle wheel" particles that convey the vortices' rotation from one layer to the next. With the spinning of the vortices representing a magnetic field and the motion of the idle wheel particles corresponding to an electric current, Maxwell's model could reproduce the main features of the electromagnetic field remarkably well.

The first installment of Maxwell's long paper describing his model, "On Physical Lines of Force," appeared in the *Philosophical Magazine* in the spring of 1861, not long after he had moved to King's College London as its new professor of natural philosophy. That summer he returned to his country house at Glenlair in Galloway and pondered how he might extend his model to include electrostatic forces. He found that if he made his vortex cells elastic, so that when the idle wheel particles were slightly displaced the vortices exerted a restoring force, the resulting pattern of strain in the ether would mimic an electrostatic field. Moreover, Maxwell's elastic medium could now carry transverse waves, and after making some plausible assumptions about how the vortices would respond to distortion, he found that the speed of such waves would equal the "ratio of units"—that is, the ratio between the electrostatic force between two charged bodies and the corresponding electromagnetic force between two current-carrying wires.



Maxwell said later that he had worked all of this out in the country, without access to accurate values for either the speed of light or the ratio of units. The French physicist Léon Foucault had recently measured the speed of light using a rotating mirror, and the German physicists Wilhelm Weber and Rudolf Kohlrausch had measured the ratio of units by comparing the charge on a condenser to the current produced when it was discharged. Once he got back to London in September 1861, Maxwell looked up these results and found, no doubt to his delight, that they were almost exactly equal: 193,118 miles per second for the speed of light, 193,008 miles per second for the ratio of units. He wrote about this to Faraday in October 1861 and, in a fresh installment of his paper “On Physical Lines of Force,” declared in January 1862 (the emphasis was his) that given the closeness of the ratio of units and the speed of light, “we can scarcely avoid the inference that *light consists of transverse undulations of the same medium that is the cause of electric and magnetic phenomena.*” Here were the first statements of what would become Maxwell’s electromagnetic theory of light.

In fact Maxwell had made an error in conversion factors when he first calculated both the ratio of units and the speed of light, but even after correcting the error, the match was still close enough to convince him he was on the right track. To test his theory, he now wanted to find the best possible values for the electrical and magnetic constants, and particularly for the ratio of units. As it happened, those values were just then becoming of pressing practical interest. In the wake of the failure of the first Atlantic telegraph cable in 1858 and other reverses in the nascent cable industry, Thomson and others issued calls for the adoption of a reliable standard of electrical resistance. Without it, they said, engineers could not assure quality control during the manufacture of cables, nor could they

find the exact location of any faults that might later appear in their insulation. Moreover, Thomson noted, the speed with which a pulse of current passes along a cable depends on the ratio between the electrostatic and electromagnetic units. At the September 1861 meeting of the British Association for the Advancement of Science, Thomson and his protégé, the young cable engineer Fleming Jenkin, engineered the formation of a committee to develop and disseminate a reliable standard of electrical resistance. The British Association Committee on Electrical Standards would go on to become the focus of some of the most important electrical researches of the nineteenth century.

In 1851 Weber, building on the work of his colleague C. F. Gauss, had devised an “absolute” system of electric and magnetic units in which charge, current, and resistance could be expressed simply in terms of length, mass, and time—for instance, in meters, kilogrammes, and seconds. At Thomson’s urging, the British Association Committee adopted a version of this system, with the magnitude of the units adjusted by factors of ten to suit the needs of cable engineers. In the absolute system, resistance appeared as a velocity, and Maxwell saw that such a standard of resistance could be a step toward making a better measurement of the ratio of units and so of determining whether it was really equal to the speed of light. Maxwell soon joined the British Association Committee and in 1863–64 he and Jenkin did much of its experimental work in Maxwell’s laboratory at King’s College London, joined first by Balfour Stewart and later by the young cable engineer Charles Hockin. Using a plan devised by Thomson, they rotated a coil of wire in the earth’s magnetic field and observed how a magnetized needle was deflected by the current induced in the spinning coil. They could then calculate the resistance of the coil in absolute units—that is, in metres per second—and use it to construct a standard with the desired resistance of 10

million metres per second. Initially simply called the “B.A. unit,” this soon became known as the ohm. The British Association Committee began issuing standard resistance coils in 1865; they were quickly adopted in the cable industry and later came into general use.

At the same time as he was doing this experimental work on the ohm, Maxwell set about reframing his theory of the electromagnetic field, seeking to make it as independent of the details of his vortex and idle wheel model as he could. He did not, as is often claimed, simply abandon his model; there is in fact strong evidence that he continued to believe there are real vortices in the ether. But he had always regarded the idle wheel particles as an awkward and unrealistic stand-in for whatever the real connection between the vortices might be, and in his “Dynamical Theory of the Electromagnetic Field,” presented to the Royal Society of London in December 1864, he formulated the laws of the electromagnetic field in the most general way he could, relying not on a detailed model but simply on the general principles of dynamics. His aim was not so much to throw over the vortex model as to see how far he could get without it. The answer was: pretty far, but not all the way. Notably, in “Dynamical Theory” he did not try to explain the Faraday effect, the magneto-optic rotation that had first inspired his vortex theory. As Thomson had shown, that effect required real rotation in the medium, and when Maxwell returned to the topic in this 1873 *Treatise on Electricity and Magnetism*, he again invoked vortices in the ether.

Maxwell may not have been able to explain every optical effect in “Dynamical Theory” (besides the Faraday effect, he did not attempt to account for reflection or refraction), but it was certainly a remarkable achievement. In a rare boast, Maxwell told his cousin Charlie Cay that he thought his paper was “great guns,” and it is now rightly regarded as the foundation of his theory of the electromagnetic field. But “Dynamical Theory” includes two sections that seem out of keeping with its grand sweep and are now often overlooked. One concerns condensers and electric absorption; the other focuses on calculating the mutual induction of two coils of wire. Why did Maxwell include these sections in “Dynamical Theory”? They were in fact preparation for his next experimental project, toward which he had in many ways been aiming since 1861: a new determination of the ratio of units. Working closely with Hockin, Maxwell devised an apparatus, using a parallel-plate condenser and two coils of wire, with which he could directly balance electrostatic and electromagnetic forces. The connecting link and the key to the whole experiment was the B.A. unit of resistance: as Maxwell said in his 1868 Royal Society paper “On a Method of Making a Direct Comparison of Electrostatic and Electromagnetic Force,”

In the experiments here described no absolute measurements were made of length, time, or mass, only the ratios of those quantities being involved; and the velocity determined is expressed in terms of the British Association Unit of Resistance, so that whatever correction may be discovered to be applicable to the absolute value of that unit must be applied to the velocity here determined.

In fact, Maxwell was undertaking to measure the ratio of electrostatic and electromagnetic units in terms of the B.A. unit of resistance; odd as it might now sound, he was going to find the speed of light in ohms. After a series of measurements, Maxwell arrived at a value for the ratio of units of 28.8 ohms, or 288,000 kilometres per second. This was close to Foucault’s value for the speed of light, 298,000 kilometres per second, but not quite spot on. As Maxwell had noted, any error in his and Jenkin’s determination of the B.A. unit would carry over into his value for the ratio of units, and this turned out to be the case. There were already signs in 1868 that the standards issued by the British Association Committee fell short of their intended value of 10 million metres per second, and in the 1880s Lord Rayleigh and others showed that the B.A. ohm was about 1.3% too small, mainly because of an error Maxwell and Jenkin had made in figuring the inductance of their spinning coil. In the 1890s, as physicists made better measurements of both the speed of light and the ratio of units, the two values converged, just as Maxwell’s theory had said they should.

In “Dynamical Theory” and later in his *Treatise*, Maxwell did not express his theory in the canonical set of four vector equations now found in textbooks and on the plaque at 14 India Street. These have in fact been taken from papers a later Maxwellian, Oliver Heaviside, published in the mid-1880s. Aiming for fullness rather than concision, Maxwell had instead given a list of twenty equations that included many quantities that do not show up in the compact set of four. But in a “Note on the Electromagnetic Theory of Light” that he appended to his 1868 paper on the ratio of units, Maxwell stripped his theory down to four basic laws, which he expressed in words rather than in symbols. These laws, connecting the electric and magnetic fluxes and intensities, correspond directly to the four “Maxwell’s equations.” Maxwell’s aim in this note, as he said in its published abstract, was to show “in as simple a form as he could” the reasons for “believing that the ratio of the electrical units, and the velocity of light, are one and the same physical quantity.” Here he made plain the link between his work on the ohm, the ratio of units, and the laws of electromagnetism. In this way we can see the two plaques on the wall of Maxwell’s birthplace do not mark two separate achievements, but rather two parts of his unified effort to grasp the workings of the electromagnetic field.

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EXPLORING MAXWELL'S HAUNTS IN AN IMMERSIVE VIRTUAL WORLD

Colin Murray, with James Gentles

and opening and closing remarks by Catherine Booth

Introduction – a word from the Foundation

We at the James Clerk Maxwell Foundation are always aware that despite our best efforts, Maxwell is still not as well-known as he ought to be, even in his native country. People have usually heard of Newton and Einstein - so why not Maxwell? We advertise and conduct tours of his birthplace home, and tell his story at every opportunity - but maybe that isn't enough. We should be doing more to promote his name to the wider public - and that means exploiting our online presence more imaginatively - but how?

With this in mind, you can imagine the enthusiasm which Foundation Trustees felt, when in 2023 a creative and exciting project proposal was made to them by Foundation Fellow, James Gentles!

After a long career working for Hewlett Packard making communication test equipment, James spent the final decade running his own successful microbusiness. He designed and built specialist parts to control cameras remotely for use in motion and aerial photography. These products sold globally for major camera brands.

James had already produced a virtual Tour of India St and the interior of No.14 in 2017, so the Foundation knew of his ability and talent for such work. His proposed new project was much more ambitious, and now, where we are in spring 2026, it's close to fruition, and we can hardly wait!

We are lucky at this stage to have been allowed to preview here some of the photographs used in the project, giving us a tantalising taste of what the final product will look like. Most exciting of all are the views inside the shell of the large house at Glenlair, destroyed by fire in 1929 and later roofed and stabilised. The current owner of Glenlair, Captain Duncan Ferguson, generously allowed James's Team access to this building, which will give even long-term Maxwell enthusiasts a unique look inside the restored structure.

Below is the story of the project, as James, collaborator Colin Murray, and others in the Team would describe it. The Foundation is hugely indebted to the many people involved in this exciting forthcoming development for their generosity, dedication and commitment. Members of the Team have volunteered hundreds of hours on the project, a significant effort.

Outline of the project

Here we explain what the forthcoming virtual Tour will provide and highlight the new opportunities the project offers to understand and communicate (we hesitate to say understand) the work of Maxwell to a global audience.

The project consists of an extended version of the existing India St virtual Tour, which already covers the inside of Maxwell's house at 14 India Street in Edinburgh



Image 1: Maxwell and locations in Scotland, extracted from his Virtual World

(now his museum) and the many significant artefacts held there. The new Tour will build on this to include notable locations in Maxwell's life. The Team has therefore visited Edinburgh churches where he worshipped frequently, his school at Edinburgh Academy, churches with which he was associated in Galloway, and his Glenlair country estate with the small museum there dedicated to him, plus his original dwelling. Like the existing Tour of India St, the Team has used panoramic photography, taking thousands of very high-resolution photographs to create 360°-images of places which visitors would not normally see. These images can be enlarged or zoomed-in to inspect detail with great clarity, for example handwritten notes, text, or a drawing hanging on a wall.



Image 2: The entrance hall of 14 India St. with 'Toby' offering a welcome (from the original Virtual Tour).



Image 3: Exhibition Room 1 at 14 India St. (from the original Virtual Tour).



Image 4: The manuscript of Maxwell's paper on ovals, on display in Exhibition Room 1 (from the original Virtual Tour).

The new Tour will enhance the existing content, scope and functionality quite significantly. A viewer will quickly and easily be able to wander through the many areas on offer and gain a general view of Maxwell the man, his work, and the environment he saw in his lifetime. Areas can then be revisited and explored in detail where there is specific interest. Information pop-ups have been authoritatively written, many by Foundation Curator and former Trustee, John Arthur. One example is the George Street Maxwell statue where the bronze friezes are explained in detail. These carvings tell the story of the history of physics in a fascinating manner with key historical figures. There are approximately forty areas or 'worlds' that can be explored in great detail within the new Tour.

Engagement

The expected audience for the Tour includes professional readers, historians, casual viewers, schoolchildren (of all ages) and their educators. A quiz is provided to encourage younger viewers to seek out items of interest by navigating the virtual world. With a mixed on-line audience, we anticipate different levels of interest and knowledge, but, very importantly, everything has to be as factually accurate as possible. Links to further resources are being incorporated for the user who wants more information. Engagement with the Tour is designed to be easy, intuitive and instant, on whatever device is being used.

The virtual Tour will be viewable on any PC browser, tablet, or smartphone, or a 3D headset and will be accessed from the Maxwell Foundation website.

Why do this now? Why not use Google? Why not use Artificial Intelligence?

Indeed, these are valid questions. Now is a good time as significant dates in Maxwell's life are approaching, such as the 150th anniversary of his death in 2029, and the 200th anniversary of his birth in 2031. Surely these need to be widely publicised and celebrated.

Google Earth is already used on the Foundation website in two well-constructed Tours which allow visitors from afar to view Maxwell's birthplace, his haunts in Edinburgh, the region in Galloway where he grew up, and other locations of interest in his background and life. These tell Maxwell's story and present images in a unique way and complement each other.

But this new Tour is different. The vision was to celebrate Maxwell's life and work by photography beyond his birthplace in India St. A key idea was to concentrate, with a few exceptions, on viewpoints which Maxwell himself would have seen, reaching into interiors of the other chosen locations in Edinburgh and Galloway.

Because the information presented within this virtual Tour has been fully curated back to known sources of evidence at every possible opportunity, the Tour can be used with confidence as an academic reference point for source materials and is not dependent on what Artificial Intelligence may randomly retrieve. It is initially English-language based but is designed to be upgraded later for a multilingual audience if there is a demand.

Navigation through the Tour

We have aimed to make navigation through the Tour fun, and tried to make the views as realistic as possible, all with authentic photographic backgrounds. Extra 'buttons' and automatic highlighting of selected areas are added onto the view to enrich the experience. These can be ignored by viewers who simply want to explore each scene, and wander through the house, school, churches or the Glenlair estate. However, if a viewer wishes to know more about, for example, the person in a portrait, or a detailed explanation of the frieze on the Maxwell George Street statue, they can do so.

There is no single linear route through the Tour. Each viewer's journey will therefore be different. Locations are linked in multiple ways, and one click can whisk you from Edinburgh to Galloway if you choose.

Seeking inspiration, then and now

The Team naturally took the opportunity to stand on the spot outside the Glenlair ruin, where it is believed Maxwell used to gaze out onto his estate while pondering things scientific. Apparently visiting scientists have been known to emulate this behaviour, to what effect we will never know!



Image 5: The exterior of the house at Glenlair, the main building being now a shell. The facing vestibule door leads to a small Museum dedicated to Maxwell's life and work.

Looking up at the ruin, the second-floor window is where we speculate Maxwell gazed out while pondering some of his greatest works. With no floor remaining, this vantage point remains unvisited by any hopeful scientists these days, but can be viewed in the Tour!

Maxwell spoke of walking along the nearby river Urr – perhaps also to seek inspiration – and this river features in watercolours painted by his cousin, Jemima Blackburn, which are on display in India St. The Tour view includes seats and a first edition of Maxwell's *Treatise on Electricity and Magnetism* (1873), largely written at Glenlair.

Capturing Maxwell the man, the scientist and the polymath

As well as his science, other facets of Maxwell's life were very important to him. The Team felt it was critical to convey an impression of the whole of his personality.



Image 7: Virtual Tour view of the small museum inside the vestibule at Glenlair, with its geometric patterned mosaic floor designed by Maxwell.



Image 6: The inside of the house at Glenlair, which suffered a serious fire in 1929. It was subsequently re-roofed and stabilised, but is still a shell not normally accessible to visitors.

Religious faith

All his life Maxwell had a strong Christian faith, from which he never wavered. Religion was a very significant part of his life and as important to him as his scientific work. Growing up, he was influenced by both his father's Presbyterianism, and his aunt's embracing of the Episcopal church.

Maxwell lived at a time of schism in the Church of Scotland and the details of his worship are complex. While living in Edinburgh he attended both the Presbyterian St Andrew's Church on George St where he was baptised, now known as Edinburgh New Town Church, and St John's Episcopal Church on Princes St.



Image 8: Virtual Tour view of the current New Town Church in Edinburgh, with its oval design which may have helped to inspire Maxwell's interest in oval curves

At Glenlair, the family were deeply involved in the life of both Parton Kirk and Corsock Kirk, itself subject to the schism. The building which was Corsock Kirk in Maxwell's

time is now a private dwelling, but memorials to Maxwell which were in that building were moved to what is at present Corsock Parish Church. Despite schism in the church, for Maxwell his faith and science were integral parts of his own being.

The Tour therefore includes photographs taken with permission within all these churches. An extra touch in Corsock shows a bible open at one of Maxwell's favourite verses. The church details explaining the schism and its impact are part of the Tour.



Image 9: The Virtual Tour creative team in action in Parton Church, Galloway, a church associated with the Clerk Maxwell family, and beside which Maxwell's grave is located.



Image 10: Maxwell's grave beside Parton Church with stand-in 'Toby' sporting a tartan ribbon, to represent Maxwell's demonstrations of colour reproduction.



Image 11: Interior of Corsock Church built as a Free Church in 1851-52. This was not the church which Maxwell attended; that one was converted into a private dwelling and memorials from it were removed and installed here, including the stained-glass window dedicated to him.



Image 12: Stained glass window in honour of Maxwell, now in Corsock Church.

Poetry and music

Maxwell enjoyed writing poetry, often with a humorous tone. Some of his poems were written as the words to songs, often closely related to familiar Scottish songs. Inspired by these, a group of musicians, coordinated by the Orkney Science Festival in 2014, created a CD, *Music for Maxwell*. The Tour, at various places, incorporates extracts of this music, as well as other musical pieces.

Maxwell's demonstration on colour reproduction

Maxwell is famous for being the first to demonstrate a permanent coloured image in his 1861 presentation at the Royal Institution in London, based on his original concept of the red-green-blue additive mixing technique. This is usually recognised as the first demonstration of colour photography.

Here is an analogy with the Tour, in that it uses a mathematical solution to exploit photographic images to create 360x180 degree views. The combination of mathematics and photography seems appropriate for Maxwell's scientific interests. The Team believes that Maxwell, with an interest in optics and scientific developments of his own time, would thoroughly have approved of creative photography being used in our day to promote his life and legacy.

Overcoming obstacles – or as Maxwell would have said – “What’s the go o’ that?”

As with many projects, the work to deliver the solution was significantly more than envisaged, the technical problems were greater than anticipated, and the details to be curated academically and placed in context were complex and time-consuming. The key driver or ‘glue’ holding the Tour together is the baseline volume of 98,000 very-high-resolution photographs, all stitched together panoramically with specialist software into various scenes. Anonymity had to be respected, with cars removed or number plates changed. Modern accessories - wall sockets, lamp posts,

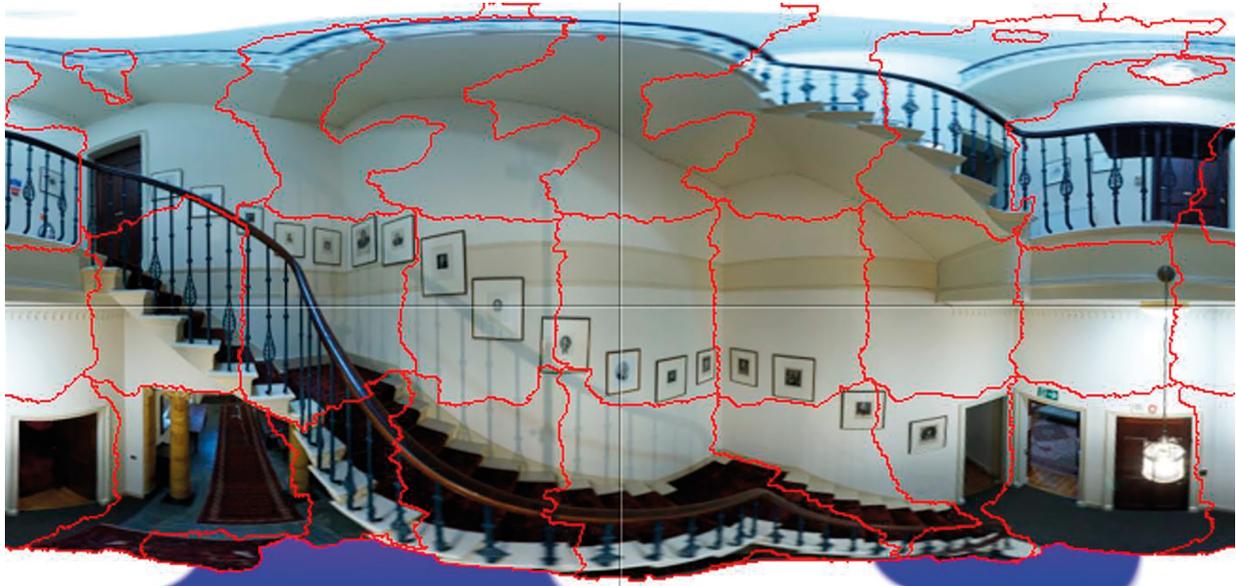


Image 13: Stitching together 98,000 photos: how it's done

security sensors, TV antennae etc. had to be deleted. Inside the house and ruin, photography involved the erection of a stable platform, 5 metres high, to allow the correct vantage point for the entire room without introducing distortion.

Very importantly, all music and property permissions were agreed – 40 contacts were involved for the school, churches and Glenlair estate. This was a significant and onerous task.

The Team also had to cope with the complications of filming with children and animals. The correct breed of dog, thought to be an Irish terrier, was sourced via the Kennel Club and the dog's owner brought her own grandchildren, a girl of 4, and a boy of 2 into India St for the photography. A child was to represent a young Maxwell within his own house. Maxwell owned terrier type dogs throughout his life, all said to be named 'Toby', one of whom features on the statue in George St, Edinburgh.

A historically accurate costume - apparently the collar style defines the correct period - was sourced with expert help. Unfortunately, the 4-year-old girl refused to wear the garment so it was adjusted with bulldog clips to fit the 2-year-old boy. After a very long morning, the child and the dog were captured in the same shot in the correct positions. The dog, in particular, was difficult to persuade to put its head through the railings. Out of around 100 attempts, only one or two photographs were deemed acceptable. Toby the dog also appears in multiple locations within the Tour, and the built-in quiz asks for children (and adults) to find as many as they can.

Everyone involved in the project felt this was an investment for the future with a digital lifetime online of perhaps 10-20 years or more and gladly contributed to the programme of work.

Closing remarks

The Foundation is very excited at the prospect of having this additional superb feature on its website, and its launch will be highlighted as soon as it is available.

Little of the Tour material is available in any detail elsewhere in a simple and accessible online manner. The Foundation therefore considers that this project is an imaginative way to convey the memory of Maxwell's work in our modern world where communications are largely made using online tools. In particular, we hope that the Tour may motivate a younger generation to appreciate past notable science achievements and carry this inspiration on to their own lives and careers.

Acknowledgements

Thanks are owed by the Foundation to the many people involved in this project. The contributions these individuals made are fully acknowledged within the new virtual Tour online. There are too many names to credit here in any detail!

Colin Murray & James Gentles

Photo credits

James Gentles: Images 1, 2, 3, 4, 7, 8, 13

Garry Irvine: Images 5, 6,

Colin Murray: Image 10

Colin Murray and Garry Irvine: Images 9, 11, 12

About the authors and project leads

Former engineer and Foundation Fellow, James Gentles, has long been an enthusiastic advocate for Maxwell. Without his photography expertise and vision, not to mention dedicated and meticulous work, this project could never have been attempted. Colin Murray has worked in IT throughout his career, is a chartered engineer, and has delivered technical and commercial projects for clients throughout Europe. James and Colin are both radio amateurs located in Edinburgh and enjoy collaborating on technical and photographic projects.

WHAT DID MAXWELL'S MOTHER KNOW?

Isobel Falconer (from a blog of 12 April 2019)

Following a question at the end of my talk (Maxwell in Six Objects) at the Edinburgh International Science Festival, I'm thinking of writing a book series – “What Maxwell's Mother Knew,” “What Gregory's Mother Knew,” etc. They are just two of the many scientists who received their early education from their mothers – but we don't know what their mothers were able to teach them. It seems likely it was more than watercolours, the piano, and the Bible. Legend has it that Gregory's mother, whose brother (or possibly uncle – the sources are confused) was a mathematician, taught Gregory geometry. But Maxwell's mother?



Portrait of 'Mrs John Clerk Maxwell (née Frances Cay) and her son James' by William Dyce, Birmingham Museums Trust (via Wikimedia)

Tracing women's education and learning is really difficult, and I've not come up with any answers yet. But I've found out more about her maternal line than appears in other Maxwell biographies, and I've some leads for further places to look.

Maxwell's mother, Frances Cay (1792-1839) was the daughter of Robert Hodshon Cay, and Elizabeth Liddell, an artist. Frances' brother, John Cay, became a Fellow of the Royal Society of Edinburgh – there is a catalogue of his library in the National Records of Scotland. Unfortunately, the books were dispersed by auction, so tracking them would be difficult. It might be more possible to track Maxwell's own books, bequeathed to the Cavendish Laboratory, to see whether any might have come to him through his mother's family.

The Cay side of Frances' family is well covered in John Arthur's book, *Brilliant Lives*, but far less is known about the Liddell side. Frances Cay may have learnt anything she knew from her own mother, Elizabeth Liddell, an artist with connections to Archibald Skirving, Sir Henry Raeburn, and Thomas Bewick. The Liddell family seem to have been reasonably well-to-do, based in the North Shields area of Northumberland. Neil Jeffares, in his Dictionary of Panellists, guesses from their address in Dockwray Square that Elizabeth's father, John Liddell, was a ship-owner. However, John's will shows that he also had at least a farm and coal-mining interests at Shire Moor at Murton (I haven't read it all yet, the writing is difficult). The will also names two surviving sons (Albert and George) and four daughters (Sarah, Elizabeth, Barbara, Isabella). The family memorial in Tynemouth Parish church, gives their dates, married names, and those of further children who died young. Many of the Liddells or their husbands, including Robert Hodshon Cay, sold out of Murton Colliery in 1809.

Elizabeth Liddell's sister, Barbara, remained unmarried. At some point she moved to Edinburgh, possibly to be near Elizabeth, and lived at 19 Great Stuart St. Her will left most of her estate to her niece Jane Cay (i.e. Frances Cay's sister – Maxwell's “Aunt Jane”). The inventory of her estate is in the National Records of Scotland. Again, I haven't read either will or inventory yet, but they provide further possible leads to Frances Cay's background.

So, it looks as though Maxwell's mother *did* know how to paint. Although we still don't know what else she knew, we might be a little nearer finding out.

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'Vortices and atoms in the Maxwellian era'; in: *Philosophical Transactions of the Royal Society. A, Mathematical, Physical and Engineering Sciences* 377, No. 2158 (Nov, 2019).

'No actual measurement ... was required: Maxwell and Cavendish's null method for the inverse square law of electrostatics', *Studies in History and Philosophy of Science, Part A* 65-66 (2 Dec. 2017), pp. 74-86.

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FROM MARCONI TO 5G THE DEVELOPMENT OF MOBILE RADIO COMMUNICATION SYSTEMS

John Thompson and Peter Grant

In Maxwell's time the only way to communicate over long distances, such as between Britain and America, was by submarine cable. William Thomson, Lord Kelvin, one of the pioneers in cable communication and James Clerk Maxwell were involved in the committee that assisted cable development by standardising the unit of electrical resistance, later called the ohm [1]. Cable communications, provided a fixed end-to-end service. Maxwell's major contribution was his seminal 1865 publication on electromagnetic waves where he developed mathematically partial differential equations to describe the electromagnetic field in twenty equations, which have been reduced by later scientists to now only the four 'Maxwell equations' which are prominently displayed in the cobbles in front of his Edinburgh statue. What was not realised at the time was that electromagnetics would next become increasingly more important as Maxwell's pioneering theoretical work now forms the foundation of radar, navigation (GPS), wireless communication, cellular radio, medical imaging and many other systems.

It was several years after Maxwell's death before Heinrich Hertz was able, in 1888, to provide the first practical demonstration of the generation and reception of electromagnetic waves. He used a spark transmitter as the generator with a simple loop antenna detecting the generated wave. At the time this electromagnetic radiation was commonly called 'Hertzian' waves, but is now more generally referred to as radio waves. Ultimately radio wave propagation frees us from using cables or wires to communicate, enabling wireless communication, which permits *mobility* in the transmitter or the receiver or both.

Early wireless pioneers

The next major innovative step was made by Guglielmo Marconi who was the first person to use electromagnetic waves for *radio communication* [2]. Numerous investigators and inventors had been exploring wireless technologies and, in some cases, building early wireless telegraph systems. In 1894, Marconi conducted experiments with radio waves from a spark generator, building much of his own equipment in the attic of his home at the Villa Griffone in Pontecchio, Italy, Figure 1. His first detector was a coherer, based on the 1890 device originally designed by Edouard Branly, the French physicist, which was further refined in the UK by Oliver Lodge. The coherer comprised a glass tube with two electrodes filled with metal filings. When an electric impulse is received, the filings line up (i.e. cohere) to give a low-resistance conductive path permitting a bell to ring, before the coherer glass has to be tapped to scatter and reset the filings.



Figure 1. Marconi with his apparatus for 1890s long-distance radio transmissions, after Wikipedia.

Marconi initially built in 1894 a storm alarm detector based on a battery, a coherer and an electric bell, which detected the electromagnetic waves generated by lightning discharges. Marconi then progressed on to transmitting a signal from the Villa Griffone near Bologna in Italy to a distant point hidden behind a hill where the signal reception was confirmed by replying with a gunshot.

Aleksandr Popov installed his first coherer-based thunderstorm detector, Figure 2, at the Institute of Forestry in St. Petersburg on 7 May 1895 [3]. Some accounts say on 24 March 1896, Popov sent the Morse code message, 'Heinrich Hertz', via wireless telegraphy between two buildings 240 m apart at St. Petersburg University. There is a lack of substantial published evidence to verify this claim but 7 May continues to be celebrated today, in the Russian Federation, as 'Radio Day'!

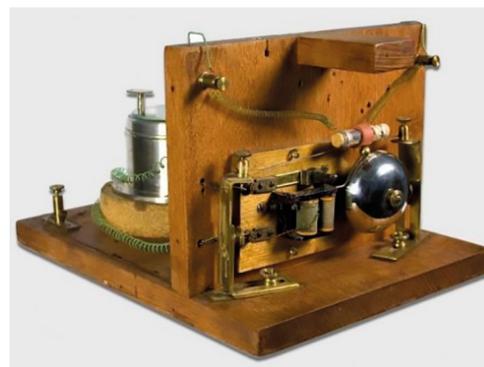


Figure 2. Popov's coherer receiver, courtesy Central Museum of Communications, St Petersburg, and *IEEE Spectrum*, May 2020 [3].

In 1895, Marconi moved on to his family estate in Bologna where he was able to transmit signals over a half-mile distance. Finding little interest or appreciation for his work in Italy, Marconi moved to Britain in 1896, as he believed it would be easier to obtain the necessary funds to convert his experiments into practical use. Marconi rapidly gained the support of the Chief Electrical Engineer of the Post Office, William Preece [4]. The Post Office, who were responsible

and research between 1900 and 1925, particularly by Oliver Heaviside and Edward Appleton, identified that there are layers in the upper atmosphere which reflect radio waves to facilitate the transmission of signals over long distances. It has been suggested [7] that Marconi had most probably generated a significant transmission around 3.5 MHz, which was much more likely to have contributed to the reflection of the transmitted signal back towards Canada.

Further developments

Today the electromagnetic spectrum is defined by internationally agreed spectral bands such as: 0.3–3 MHz Medium Frequency (MF); 3–30 MHz High Frequency (HF); 30–300 MHz Very High Frequency (VHF); 0.3–3 GHz Ultra High Frequency (UHF), 30–300 GHz Extremely High Frequency (EHF), etc and users of the spectrum are normally provided with an internationally agreed frequency allocation within these bands.

For radio communication to develop further it was necessary to provide a facility for several users to simultaneously have access to different parts of the electromagnetic spectrum. This was achieved by Fessenden first restricting the occupied spectral bandwidth of the transmitted message and then modulating the signal *amplitude* onto either side of a carrier frequency, f_c . For a speech signal, which covers the frequency range 0.1 to 4.5 kHz, the modulator generates two sidebands (SB) above and below the carrier frequency giving a total occupied signal bandwidth (BW) of 9 kHz, Figure 5. By allocating appropriate carrier frequencies, f_c , with suitable spacings to avoid the spectral overlaps, radio broadcast and communication systems can then accommodate multiple users within an allocated spectral band without suffering from interference. This arrangement is called frequency division multiple access (FDMA).

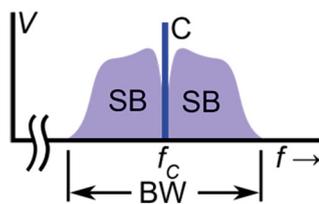


Figure 5. Spectral depiction of overall occupied bandwidth (BW) when a signal is modulated onto a carrier frequency, as two sidebands (SB), (Wikipedia).

Consider next broadcast radio. Here the medium wave band is allocated the frequencies in the HF band between 531 and 1602 kHz with individual channels spaced every 9 kHz providing for 120 possible simultaneous radio transmissions. The user then tunes his receiver to the particular radio channel, or carrier frequency, f_c , that they wish to listen to. The 4.5 kHz audio signal bandwidth is adequate for talk and news but not for high-fidelity music!

Superior quality broadcast radio uses frequency modulation (FM) where the encoding of the wider 10 kHz bandwidth analogue music signal, is achieved by varying the instantaneous frequency of the transmitted electromagnetic wave. Invented in 1933 by American

engineer Edwin Armstrong, who demonstrated his FM transmission which was totally free of static and, as a result of the wide audio spectrum being used, was received with a fidelity never heard before. His audience listened to a live music performance transmitted with remarkable clarity and even sounds of a glass of water being poured, which would have been unrecognizable over AM radio. FM is used worldwide to transmit high fidelity broadcast radio. The FM signal which is more robust against noise and interference requires a somewhat larger transmitted signal bandwidth of typically 250 kHz and this necessitates a higher operating frequency than for amplitude modulated radio. The worldwide adopted spectral band allocated for FM broadcast is usually 88 to 108 MHz, which falls within the VHF band of the electromagnetic spectrum.

Digital communication was adopted for landline telephony following the invention in 1937 of pulse code modulation (PCM) by Alex Reeves [8] in Harlow. In PCM the amplitude of the analogue signal is first sampled and each sample is then quantised into a digital codeword. Reeves invention of PCM for voice communication sampled at 8 kHz and deployed 8-bit codewords to provide a 64 kbit/s encoded data stream. The benefit of digital transmission, with either 1/-1 or 1/0, is that the received signal has only 2 states and thus it can be received at a reduced power level or signal to noise ratio. Following on from PCM many further advances in audio coding techniques are used in digital communications. For example, the simpler delta modulation technique is used in military radio communication while a more sophisticated speech vocoder [9] was used by Churchill during WW2, because it facilitated the addition of security to avoid eavesdropping.

The main attraction of wireless over cable communication is that it can be extended to permit *mobility* of the user. The first Private Mobile Radio (PMR) systems comprised a single central base station with the mobile users communicating to and from the base station. PMR is a person-to-person two-way radio voice communications system which use portable, handheld or vehicle based mobile radio terminals. These systems are still in widespread use today with taxi firms and as well as for police, fire brigade and ambulance staff. They use channels in the VHF and UHF radio bands, giving them a limited range, usually 5 to 30 km depending on terrain with an output power of less than 4 W. Because the base station antennae must be carefully located at a position that will give optimum radio coverage, it is usually installed on a hilltop tower, and coverage can extend up to distances of 50 km. In PMR individual calls are not charged, but instead the user company pays a rental for overall use of the system. These PMR systems often provided the user with a single radio channel requiring hand over where both parties can communicate with each other, but not simultaneously, as the single channel provides only communication in one direction at a time.

Further, these PMR base stations must be located sufficiently far apart to avoid interference so, in a city, the available electromagnetic spectrum is soon fully allocated making it impossible to accommodate further users. Allocated radio channels cannot be reused for more than 50 km, so the few radiated channels represented the total

communications calling capacity that is available across a city, typically 10-20 calls, servicing a few hundred users. However, the restricted number of mobile users quickly became insufficient to meet the demand and necessitated further personal communications system development.

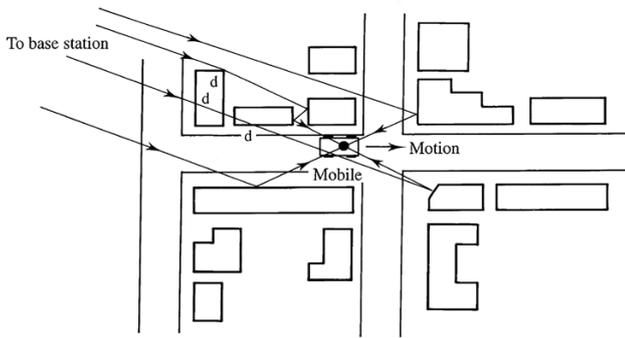


Figure 6. Origin of multipath fading arising from building reflections in a mobile radio channel, from [9].

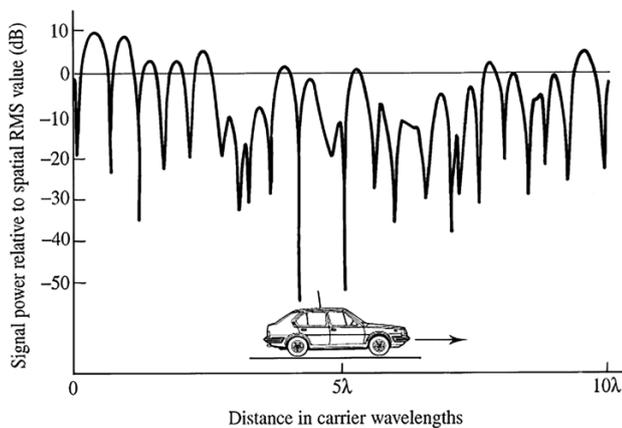


Figure 7. Typical power profile for a multipath signal as received in a moving vehicle, from [9].

One of the issues in mobile communications is that the receiver experiences not a single signal but multiple delayed copies of the transmitted signal [9] arising from the reflections from buildings and other objects, Figure 6. These multipath signals are added or summed at the mobile terminal receiving antenna. With movement in the mobile handset the coherent summation of these individual multipath signals causes the received signal power level to fluctuate or fade, Figure 7. To avoid a stationary handheld pedestrian receiver falling into a deep fade (and lose their signal reception) the transmitter and receiver are designed to regularly change the operating frequency, as this alters the received signal profile. Frequency hopping at 200 hops/s yields substantial performance gains for slowly moving pedestrians.

Cellular personal wireless communications

To increase the subscriber capacity, Bell Telephone Laboratories, in the 1940s, developed the concept of a cellular radio communications system. William Young suggested replacing the high-powered PMR transmitters with a system of low-power base-stations, each covering a hexagonal 'cell' initially as small as one square mile. These

small coverage "cells" implied that, in a fully developed system, it could require hundreds or thousands of base stations to cover a large service area but, with small cells, the radio channels could be re-used for other calls at a short distance away, effectively solving the spectral occupancy problem. Cellular communications were first documented within a 1947 technical memorandum from Douglas Ring, the team leader at Bell Labs [10]. Figure 8 from the memorandum [10] shows the proposed coverage of Long Island in New York and Figure 9 describes a 4-cell cluster repeat pattern. The system allocated individual users a narrowband frequency slot within the available frequency band, i.e. FDMA, in a similar way to broadcast radio. The cellular system requires handover capability, as the mobile transceiver moves from one cell into an adjacent cell. The switching to the new transmission frequency in the handover cell has to be performed electronically, without interruption, to maintain the ongoing continuous communication call.

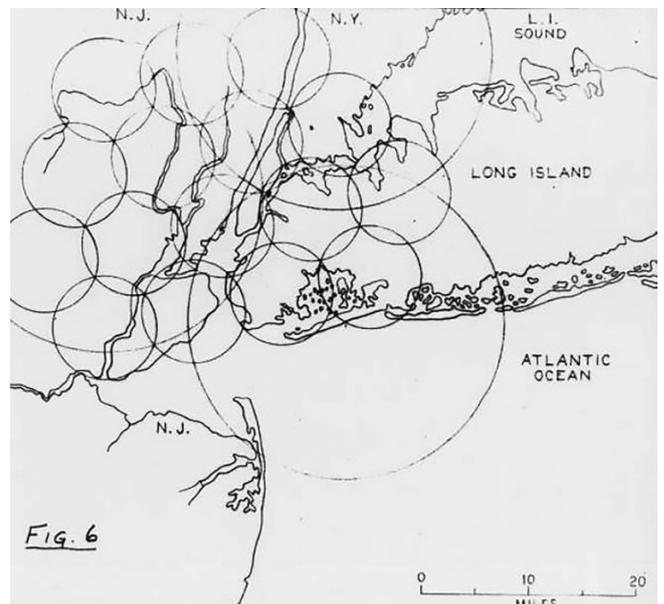


Figure 8. Proposed 1947 cellular coverage for New York and surrounding area, from [10].

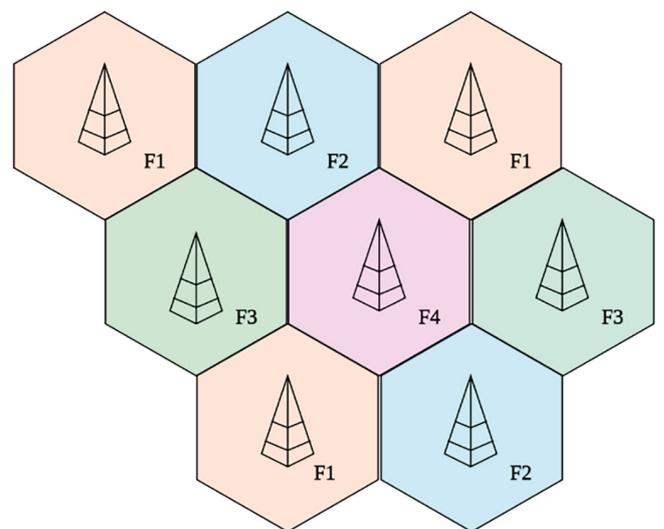


Figure 9. Example of cellular frequency reuse pattern, with four frequencies (F1-F4), after Wikipedia.



Figure 10. Richard Frenkiel, one of the key Bell Labs cellular pioneers.

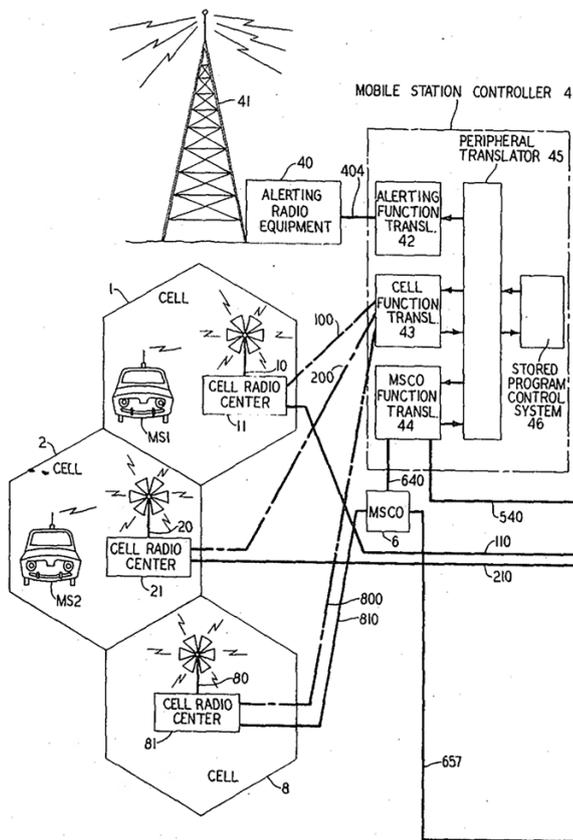


Figure 11. Diagram from Bell Labs patent showing the operation of a Cellular Communication System, after [12]

The 1947 concept then had to wait for the enabling technologies to mature. Richard Frenkiel, Figure 10, produced an influential paper in May 1970 [11] which provided the first open publication describing a cellular system. In 1971 a Bell Labs team generated the first full technical specification and definition for the design and operation of a cellular mobile communications system, patenting their design in 1972 [12]. Figure 11 shows the envisaged cellular system concept. Note here, in the 1970s, that the system was envisaged for communication with automobiles, as the mobile telephony equipment and battery were too large and cumbersome for individual or personal use, Figure 12. Bell Labs subsequently coordinated the construction and roll-out of the first trial analogue cellular telephony system in Chicago in 1978 [13]. The world's first commercial automated cellular network was launched in 1979 in Japan, providing voice communications

in metropolitan Tokyo. The launch of Japanese cellular system was motivated more by an effort to understand the issues in designing and operating a practical cellular system, rather than to generate commercial revenue.



Figure 12. Analogue 1G cellular telephone from the 1980s, courtesy Museum of Communications, Burntisland.

The US Federal Communications Commission next approved the Bell Labs designed Advanced Mobile Phone System (AMPS) standard in 1982, allocating it the spectral band from 824 to 894 MHz. AMPS started commercial operation as the US first generation or 1G cellular system, in Chicago in October 1983 offering simultaneous two-way communication between connected parties, as in wired telephony. A separate AMPS system, designed by Motorola, also operated in the Washington/Baltimore area as a full public service in 1983. Cellular communications heralded the move from *fixed* telephony, which was mainly government owned and operated, into a commercially designed and operated *mobile* system. In 1987 the IEEE Alexander Graham Bell Medal was awarded to Richard Frenkiel, Joel Engel and William Jakes, (and in 1994 Frenkiel and Engel were further awarded the US National Medal of Technology) in recognition of their pioneering work on Cellular Telephony.

Other commercial cellular systems were being installed around the world at this time. Thomas Haug, along with Östen Mäkitalo, formed the first inter-country consortium to design a common analogue mobile cellular standard which permitted *international* roaming between countries. Haug drove engineers from Denmark, Finland, Norway and Sweden to design and implement the Nordic Mobile Telephone (NMT) system [14]. NMT launched in 1981 their analogue 1G cellular mobile telephony system, which was later adopted in Benelux, Switzerland and Austria. A year later NMT enabled subscribers to have international roaming without requiring the user to change handset onto a different cellular standard as they crossed an international border into another country [14].

Total Access Communication System (TACS), a variant of AMPS, was adopted in 1983 for the first UK national cellular system, with two competing networks operated by Vodafone and BT Cellnet/O₂ [15]. With the only availability at this time being of physically large mobile handsets (the "brick", Figure 13), TACS was launched in 1985 as an expensive product aimed at the business customer. Unlike in NMT, these first-generation analogue cellular systems were

often country-specific with separate individual European standards deployed in France (RC2000), Germany (C450) etc. By 1998 these 1G analogue cellular systems had grown in popularity to serve over 90 million subscribers worldwide.



Figure 13. A 1984 British Telecom badged Motorola DynaTAC early mobile handset with primitive LED display, after Wikipedia.

In 1984 the French Director General of Telecommunications with Deutsche Bundespost launched the Groupe Spécial Mobile (GSM) collaboration to accelerate the development of a digital second generation or 2G cellular communication standard, with the French GSM delegation led by Philippe Dupuis. This Franco-German cooperation, modelled on the NMT Nordic cooperation, developed the radio access technology, which was crucial for the success of GSM. Other participants joined later, Italy in 1985 and the UK in 1986. GSM [16], as a digital system, allocated individual users a timeslot within a high-speed wideband multiplexed signal transmission, providing time division multiple access or TDMA. For the initial GSM spectral allocation, 890-960 MHz, with speech signals coded at 22.8 kbit/s, each cell can accommodate up to 475 individual telephone calls or handovers of calls between adjacent cell sites. The GSM signal processing introduced a quite tolerable overall speech delay of less than 60 ms. Due to the popularity of GSM with the general public, additional spectrum was subsequently allocated at 1710-1880 MHz which more than trebled the user capacity. This necessitated more advanced mobile user handsets, operating with the required dual band capability, but fortuitously, advances in microelectronic device capability were able to achieve this capability while, at the same time, shrinking the mobile handset size.

The James Clerk Maxwell Foundation in Edinburgh was pleased to accept from Philippe Dupuis the original French language agreement signed in May 1987 by the four government ministers with the CEOs of the two, first-generation UK cellular operators, Vodafone and Cellnet/O₂. Signed as the Bonn declaration, this formally brought together the European collaboration to design GSM, one of the first *digital* cellular mobile communications standards, with GSM later being named as the ‘Global Standard for Mobile’ communications. All of Europe got behind GSM in a rare unity guided by four public officials: Armin Silberhorn (Germany), Stephen Temple (UK) [17], Philippe Dupuis (France) and Renzo Failli (Italy) with the Finnish prime minister making the first GSM call on 1 July 1991.

GSM was so successful that the TACS system was forced to close in 2001. By 2011 the number of international mobile GSM connections exceeded 5 billion, recognising the wide acceptance of the GSM architecture which facilitated roaming and allowed calls to be made and received in over 220 countries at an affordable price for personal travellers. Thomas Haug and Philippe Dupuis’s seminal contributions to cellular telephony were recognised in 2018 by their award of the IEEE/RSE James Clerk Maxwell Medal, Figure 14.



Figure 14. Philippe Dupuis and Thomas Haug receiving their 2018 Maxwell Medals at the Royal Society of Edinburgh from the then IEEE President, James Jefferies, courtesy RSE.

Following the success of GSM, a new modern standard for *digital* PMR was developed as the European Trunked radio Network or TETRA. The development of this standard during the 1990s, particularly for the police and emergency services, relied on the support of the European Commission and was allocated frequency bands around 420 MHz and 875 MHz.

The Japanese 2G Personal Digital Cellular system was completed in 1991 with commercial service starting in 1993, slightly after GSM. Although this system was only found in Japan, its penetration accounted, at one time, for over 10% of the world market for 2G mobile phone users. The Japanese elected to have their own 2G standard, to encourage the development of Japanese handsets and base station equipment, but this inhibited somewhat Japanese equipment sales into the GSM worldwide system.

This era also saw the emergence of Short Message Service (SMS) which allowed cellular users to send brief text messages to one another. The first SMS message, sent in 1992, marked the beginnings of *digital data* transmissions in these cellular communication systems. GSM initially provided for only a limited 9.6 kbit/s data traffic capability.

At this time, individuals and companies were starting to connect their computers to the developing internet. They initially added a dial-up data modem to their wired telephone connection, where data was encoded in audio tones which could be readily transmitted over the telephone system, providing an initial data rate of 2.4 kbit/s, rapidly increasing to 56 kbit/s [9]. Subsequent

developments of the Digital Subscriber Line WiFi transmissions signalled at much higher data rates, initially at 2 Mbit/s progressing rapidly to many hundreds of Mbit/s, especially after fibre optic exchange connections were introduced. This enhanced data-rate capability-enabled high-speed video transmissions, facilitating the downloading of TV and catch-up player programmes. With the advent of digital TV many households moved from using rooftop antennae to receive wireless TV transmissions to watching internet TV, delivered via their telephone connection. With this enhanced capability in fixed communication networks a rapid demand grew for cellular networks to progress from being predominantly speech communication to providing a high data rate *mobile* capability.

Figure shows the development of cellular standards beyond the initial pioneering work on AMPS and NMT. Andrew Viterbi and Irwin Jacobs developed in the USA a 2G mobile standard based on code division multiple access (CDMA). CDMA is a radio channel access method where users are allocated a unique code within a wideband common channel (replacing the GSM timeslots) as is used in the 2G cdmaOne and the later 3G CDMA 2000 standards, Figure 15. Viterbi also made major contributions to correction of received signal errors in digital transmission, as used in forward error correcting or convolutional coders, with his Viterbi decoding algorithm now being widely deployed. Viterbi and Jacobs, who formed the highly successful US semiconductor company Qualcomm, were recognized for these pioneering developments as the first recipients of the 2007 IEEE/RSE James Clerk Maxwell Medal.

Although the 2G standards were designed predominantly for voice calls it was soon recognised that there was a need for much higher data rates than 9.6 kbit/s so that the developing use of home and office WiFi access to the internet could be expanded to mobile handsets. GSM was later extended with GPRS and EDGE, Figure 15, from a circuit switched service to packet data and this enhanced the data carrying traffic capability to 56 kbit/s.

The next step was the Universal Mobile Telecommunications System (UMTS), a 3G mobile cellular system.

UMTS united many different international mobile communication standards into a common 3G standard. While some of the UMTS pioneers thought that their 3G standard was going to replace GSM, the concept evolved for a smooth evolutionary transition that has now been followed from GSM to 3G and on to 4G and 5G. 3G UMTS specified a complete network system, which included the radio access network, the core network and the authentication of users via their subscriber identity module or SIM cards. UMTS further enhanced the data transfer rate up to 2 Mbit/s which enabled the first mobile internet access for video signal transmissions, enabling TV to be delivered direct to mobile handsets.

Since the 1990s, further advances in microelectronic device integration have enabled much more capability or signal processing and computing to be incorporated in the component circuits and it has further reduced the size of the mobile handsets. The camera phone was first introduced in the Sharp SH04 handset in 2000 [17]. These advances expanded cellular communications into a

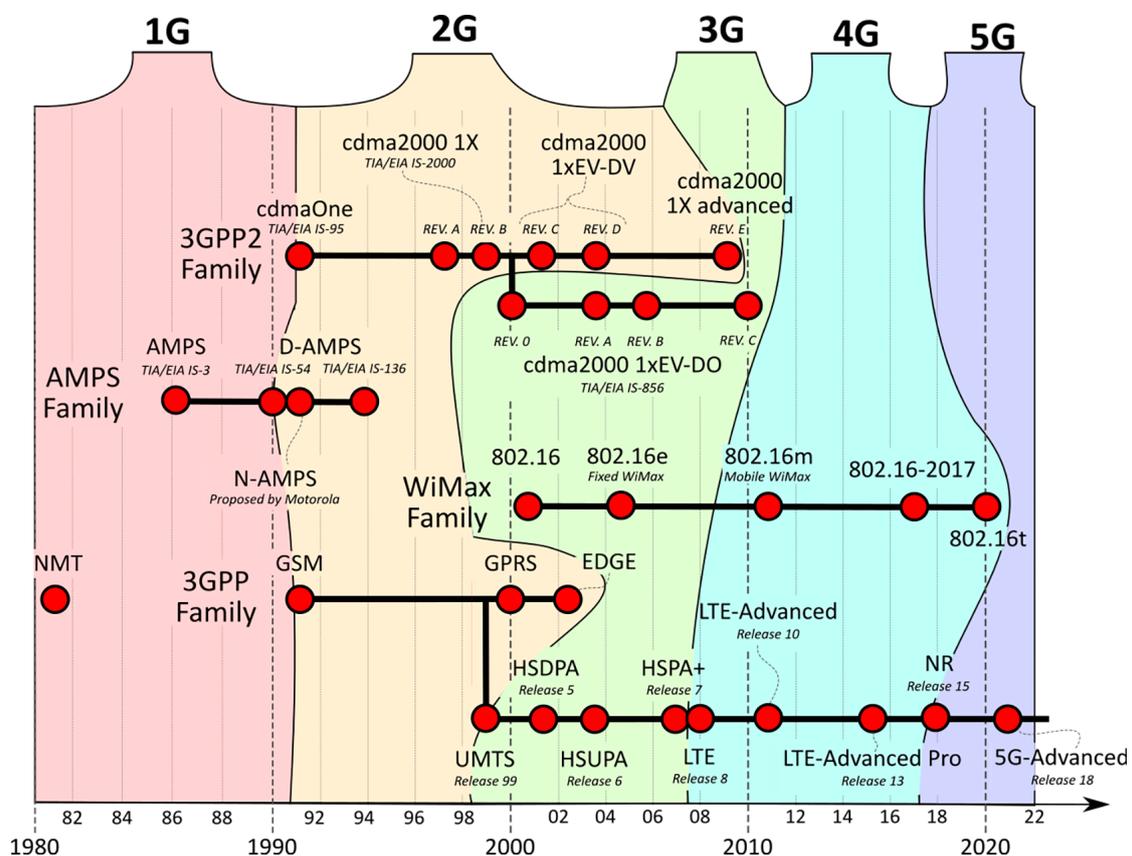


Figure 15. Evolution of cellular mobile communication standards with associated generation timeline, after Wikipedia.

worldwide system of 'personal' portable communication devices with digital signalling, text messaging and now full data transmission to enable mobile internet access for a wide range of new applications.

With significant 3G data transfer capability it soon became possible to incorporate qwerty keyboards into the handset. The first mobile handset with a full keyboard to enable internet connectivity and wireless email, the Nokia Communicator Figure 16, was released in 1998, creating the business smartphone. The first mobile internet service was launched in Japan in 1999 as i-mode by NTT DoCoMo. Another popular early business smartphone was the BlackBerry which also provided, from 1999, email and other services. At its peak in September 2011, there were 85 million BlackBerry subscribers worldwide. However, BlackBerry lost its dominant position in the market due to the introduction of touchscreen technology.



Figure 16. Nokia Communicator 9110, one of the first QWERTY keyboard mobile handsets for sending and receiving message data over the mobile internet, after Wikipedia.

Apple's first 2007 iPhone incorporated a 3.5-inch multi-touch display technology, dispensing with physical keypads. This launched the development of many different smartphones running on iOS, Android and Windows operating systems. Smartphones also launched the development of the mobile software application or app, simplifying the customer interface. With significant take up of the mobile internet it soon became clear that the 3G data transfer capability of 2 Mbit/s was insufficient to meet the public demand.

The 4G long-term evolution (LTE) standard, as developed by the 3rd Generation Partnership Project, was finalized in 2008 as the follow-on mobile cellular communication standard, which was based on the further evolution of the GSM and UMTS standards. One of the features of 4G is that it deployed, for the first time, the multiple-input and multiple-output (MIMO) antennae technique. This multiplies the capacity of the radio link by using several antennae at both the base station and the mobile handset. MIMO sends and receives several data signals simultaneously over the radio channel by exploiting the differences in the signal propagation characteristic from the various multipath modes at each of the receiving antennae. With 4 transmitting and 4 receiving antennae this can offer up to 16 possible transmission paths which provided data rates up to 20 Mbit/s. MIMO techniques were also incorporated into the indoor WiFi wireless standards. 4G

was further able to accommodate relatively low data rate traffic for the Internet of Things (IoT) which facilitated the interconnection of low-rate sensors such as medical devices and home automation which is not that demanding on latency or transmission delays.

With cameras integrated into smartphone handsets, Robert Henderson at University of Edinburgh, developed and patented a novel photon detector [18] which was subsequently used in the design of a smartphone camera rangefinder. An emitter sends infrared photons which are reflected by the target and detected back at the receiver. Measuring the time difference between the photon emission and the reception provides the distance to the target in mm, with a high accuracy. This component ensures that the user is never required to manually focus the handset camera! Without semiconductor processing or fabrication capability this innovation could not be exploited commercially by the University. Henderson's patent portfolio was thus assigned to the European semiconductor manufacturer, ST Microelectronics, enabling them to develop their laser camera auto-focus component, subsequently marketed as their FlightSense™ product [19]. This component was so commercially successful it has now been integrated into over 170 different models of smartphone and has shipped, today, more than 3.5 Billion devices!

5G, the fifth-generation technology, which is known formally as the International Telecommunications Union (ITU) standard IMT 2020, began deploying worldwide in 2019. The 5G networks, which operate in allocated spectral bands at the higher carrier frequency of 3.4 GHz, offer not only higher download speeds of 100 Mbit/s for base to user and 50 Mbit/s for user to base, but they also provide significantly lower 1-4 ms processing delay enabling, for the first time, near-instantaneous mobile communication. Low latency enables 5G to be deployed in applications requiring real-time data exchange, such as augmented reality, autonomous vehicles, remote medical surgery and industrial automation. Part of the significant increase in data rate comes from the move to even smaller cell sizes. Small cells are categorised as: microcells with less than 2 km radius; picocells at less than 200 m; and femtocells at around 10 m. These smaller cell deployments enable a major increase in data rate capability but they incur a significant extension in the required number of cell site backhaul connections and they can introduce further handover issues. (In the United States, 5G has a further microwave frequency allocation at 26 GHz to enable even higher Gbit/s data rates but this allocation has not been introduced elsewhere.)

The next 6G, sixth generation technology, will be based on further improvements in the radio interface, modulation and coding techniques, and aims for roll out in early 2030s to offer further increases in data transfer rates over the previous generations.

Summary

Maxwell and Hertz introduced the possibilities of generating and receiving a wireless signal transmission. Marconi next demonstrated how to construct a fixed point to point telegraphy system and, if one of the end stations was located

on a ship, then it provided initial mobility. He was the astute businessman who designed and operated many of the first international wireless communication systems. Today we have come a long way from these early systems. With the technical advances in signalling and signal processing, combined with the developments in microelectronic device capability, this has provided a reduction in equipment size, enabling us to have pocket sized personal handsets which combine worldwide wireless connectivity with high data rate capability to offer many services which were only dreamed as possibilities as recently as the 1980s.

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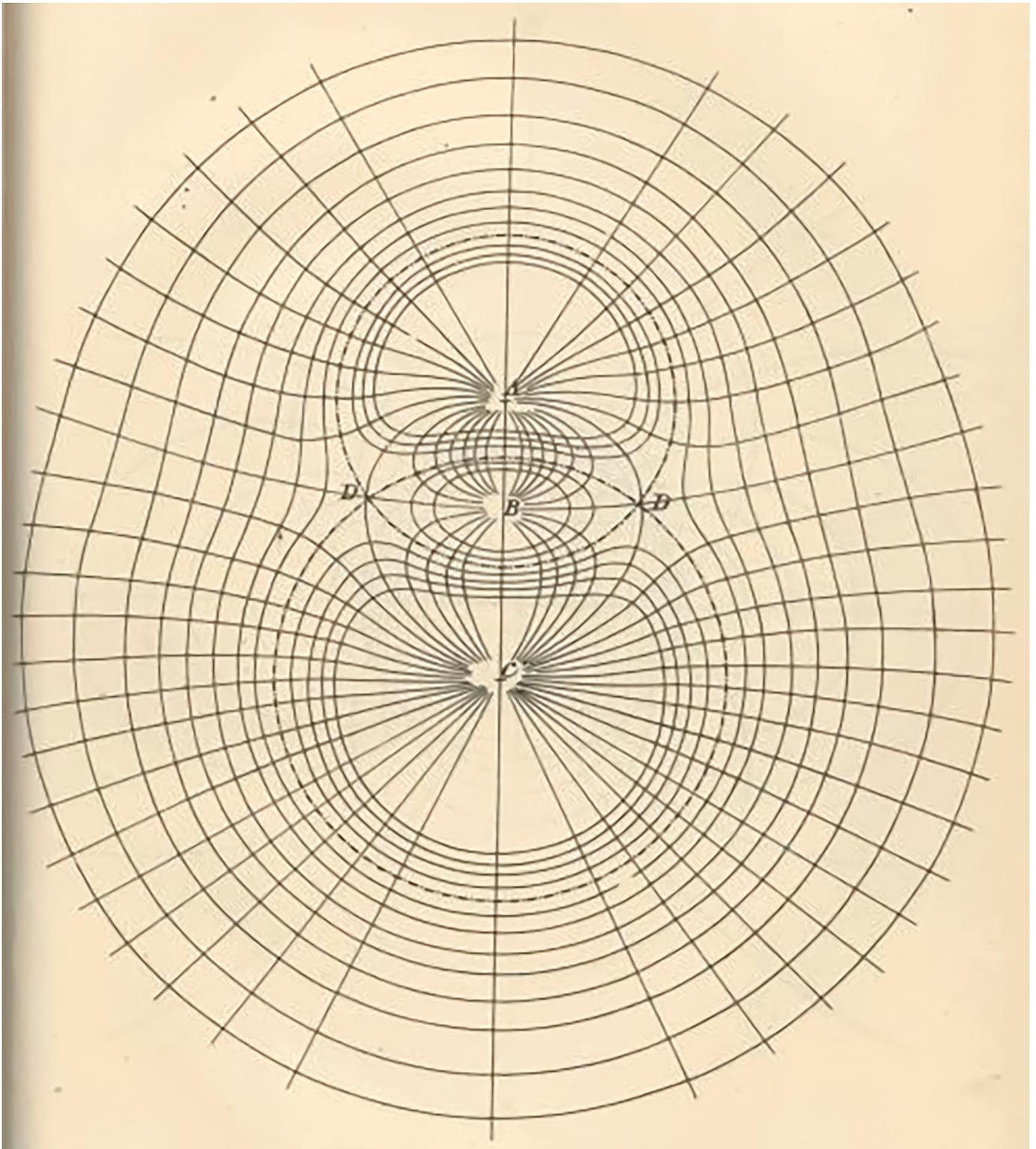
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