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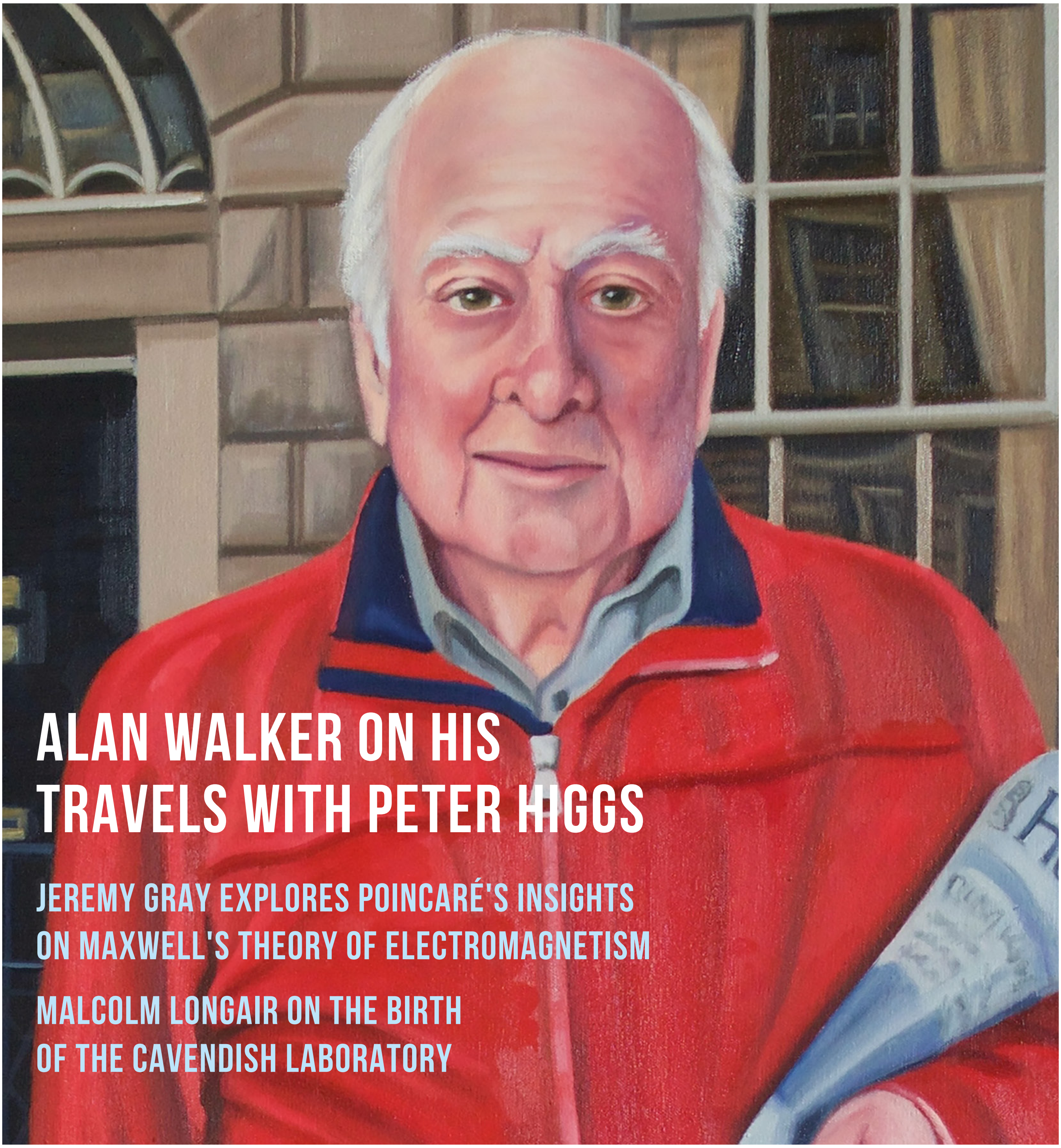
The Maxwellian

THE JOURNAL OF THE JAMES CLERK MAXWELL FOUNDATION



ALAN WALKER ON HIS TRAVELS WITH PETER HIGGS

JEREMY GRAY EXPLORES POINCARÉ'S INSIGHTS ON MAXWELL'S THEORY OF ELECTROMAGNETISM

MALCOLM LONGAIR ON THE BIRTH OF THE CAVENDISH LABORATORY

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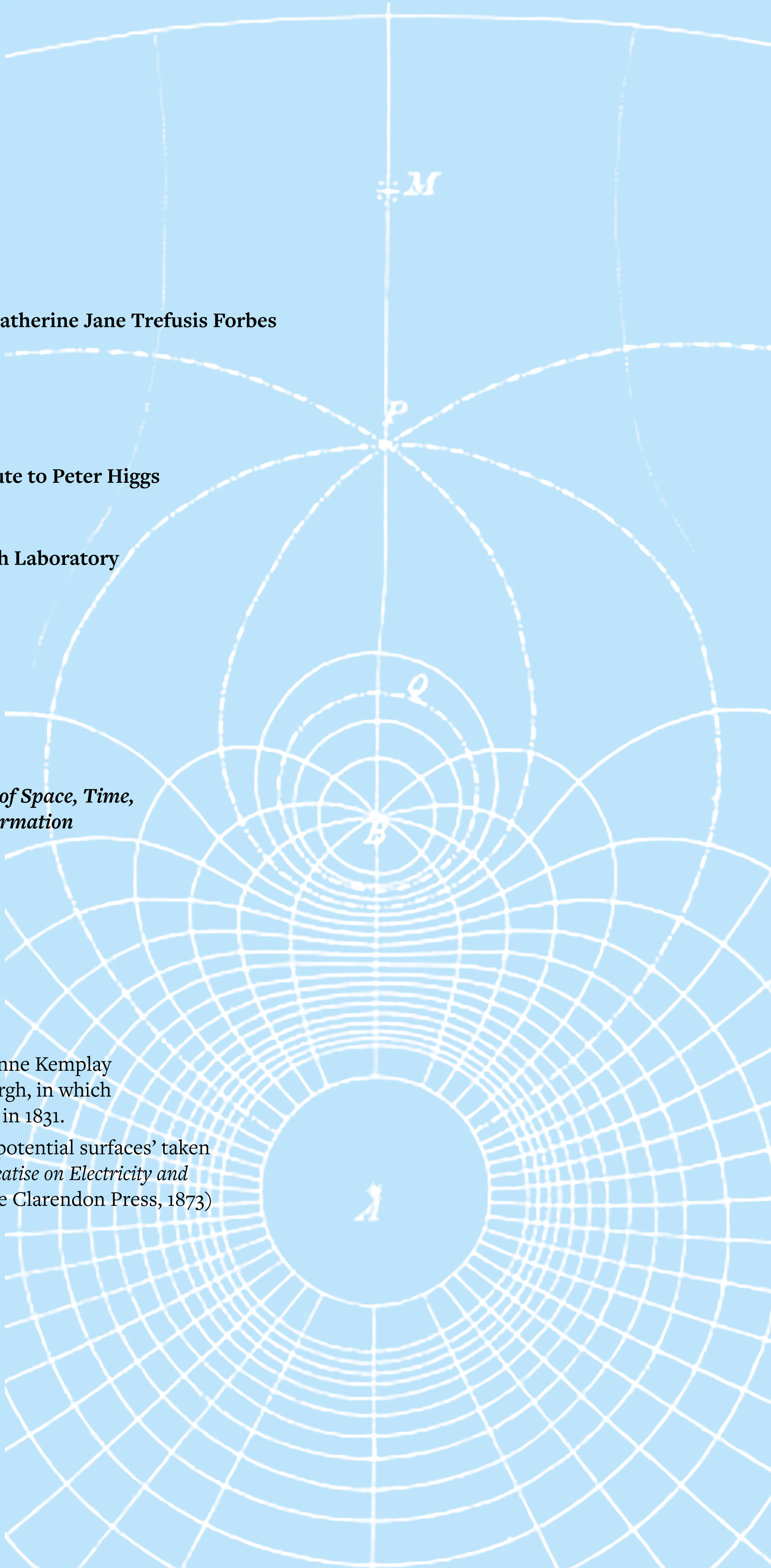
Front: Portrait of Peter Higgs by Suzanne Kemplay outside 14 India Street, Edinburgh, in which James Clerk Maxwell was born in 1831.

Back: ‘Fig. II. Lines of force and equipotential surfaces’ taken from James Clerk Maxell, *A Treatise on Electricity and Magnetism, Vol. I* (Oxford, at the Clarendon Press, 1873)



EDITORIAL TEAM

EDITORIAL

Chris Pritchard

Welcome to the second issue of *The Maxwellian*, a journal with a focus on the life and scientific legacy of the Scottish physicist, James Clerk Maxwell. We were gratified by the reception given to the first issue which was largely on the history of radar, and we start this issue with a brief follow-up on Robert Watson-Watt and his wife, Jane Trefusis Forbes. Maxwell's influence was felt during his short lifetime and in the period immediately afterwards but, as well shall see in this issue, it is still being felt today.

Until a short time before his death, Peter Higgs was the Honorary Patron of the James Clerk Maxwell Foundation. In 2013, he was the toast of the scientific community, celebrated as a Nobel Laureate for his prediction of the Higgs Boson. In this issue's opening article, Alan Walker, his close colleague and confidant, paints a picture of what it was like to work and travel with him during those years of vindication and acclaim – a very human story, both humorous and touching. And we hope you like the portrait on the cover, painted by Suzanne Kemplay and now on display at 14 India Street.

We learn of Maxwell's influence on Henri Poincaré in an article by Jeremy Gray, the distinguished historian of mathematics and biographer of the French mathematician and physicist. Jeremy explains which elements of Maxwell's electromagnetism found their way into Poincaré's *Électricité et Optique*, and why.

And we are grateful to Malcolm Longair for an article on the funding and the founding of the Cavendish Laboratory in 1874. This is the story of the need for such a facility at Cambridge, the Duke of Devonshire's largesse, Maxwell's appointment as the first Professor of Experimental Physics at Cambridge in 1871 and his personal supervision of the design and fitting of the laboratory.

We close with a review of Robyn Arianrhod's wonderful book, *Vectors*, which traces the history of vectorial methods from even before Hamilton's quaternions right through to the present-day. When was the mathematics driving the physics and when was it the other way round? Of course, Maxwell features large but there is also a telling cameo from Peter Higgs.

AIR COMMANDANT DAME KATHERINE JANE TREFUSIS FORBES

Catherine Dunn

Reading about Robert Watson-Watt in the first issue of *The Maxwellian* prompted me to seek out his final resting place in the graveyard of the Episcopal Church of the Holy Trinity in Pitlochry. The gravestone revealed another link to Maxwell.

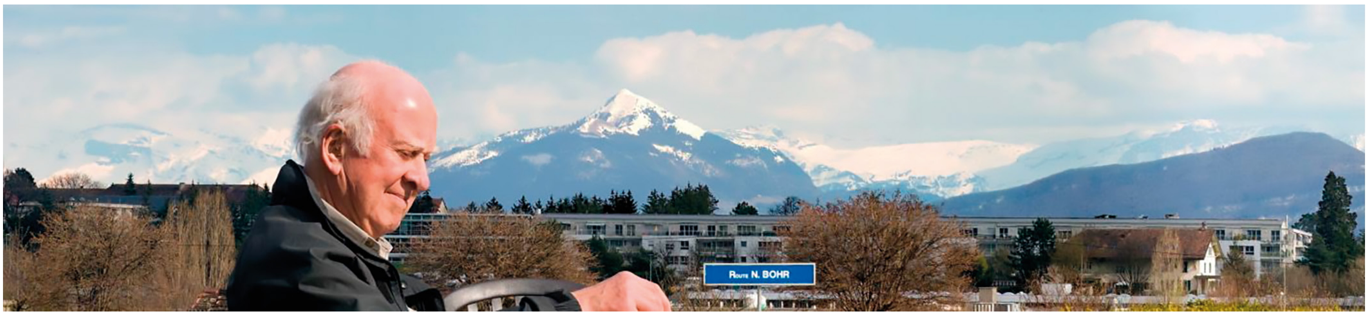
Watson-Watt's third marriage, in 1966, was to Katherine Jane Trefusis Forbes (1899–1971). Jane, as she was called in the family, left school and volunteered for the Woman's Volunteer Reserve. She had been promoted to Director of the Women's Air Auxiliary Force (WAAF) by the start of World War Two, a force which would grow to 175,000 by 1943. She then visited allied countries to encourage them to set up a similar force. Not only did she hold the rank of Air Commandant but George VI elevated her to a Damehood. Wartime radar operators were supplied by the WAAF during the war and it could be that Watson-Watt met her at this time.

Photograph via Wikimedia: Imperial War Museum non-commercial licence.

Jane was the granddaughter of James Forbes, whose lectures Maxwell attended and who gave him free use of class apparatus for original experiments. It was Forbes whom Maxwell's father asked to comment on his son's first paper, "On the description of oval curves." Forbes was impressed by the paper commenting on its ingenuity and offering to present it to the Royal Society of Edinburgh. That was the start of a long friendship. Jane inherited the Observatory at Pitlochry from her uncle, George Forbes, who had it built there for dark skies. George was an electrical engineer and an astronomer. He invented the carbon brush, a vital component in generators, while holding the Chair of Natural Philosophy at Anderson's College (now Strathclyde University). Jane and Robert lived in the house attached to the Observatory after they married.

TRAVELS WITH PETER: A TRIBUTE TO PETER HIGGS

By *Alan Walker*



Introduction

I first met Peter in 1969 at my interview for a lectureship at the Tait Institute for Mathematical Physics in Edinburgh. Peter was on the interview panel, and I was appointed. I guess I got lucky!

Early life

Peter Ware Higgs was born in Elswick, Newcastle upon Tyne on 29 May 1929. His paternal family came from Bristol. His father, Thomas Ware Higgs, moved there from Bristol to set up local radio for the BBC. His grandfather, Albert Ware Higgs, was a dispensing chemist in Bristol. His great-grandfather, Richard Higgs, was a wealthy maltster who married Ann Ware. John Higgs, his great-great-grandfather was a publican at the Waggon & Horses in Stapleton Road, Bristol.

Peter's mother, Gertrude Maud Coghill, came from Hopesay in Shropshire. His grandfather, John Davidson Mackay Coghill, was a physician from Edinburgh. His great-grandfather, John Coghill, was born In Thurso Caithness and joined the Lifeguards, protecting the monarch at Windsor Castle. John Coghill retired to Edinburgh and became a spirit dealer on Bank Street.

Thomas Ware Higgs was moved by the BBC to Birmingham in 1930. Peter went to a variety of private primary schools and to Halesowen Grammar School in 1939. As World War II began and Thomas was moved again, this time to Bedford, Peter went with his mother to stay in Bristol for 'safety'. In fact, the centre of Bristol was 'blitzed' the day before they arrived. Peter told me that he fell and broke his arm in a bomb crater in his school playground. On a walk with his mother along the River Avon they were close to an army lorry attacked from the air, but fortunately they were unscathed. At Cotham School, Peter was fascinated by Dirac's name that appeared several times on the honour boards. He found himself a hopeless experimenter, so decided to pursue mathematics. Peter moved to London in 1946 to study mathematics at the City of London School.

Family photographs of Peter Higgs in Birmingham: age unknown in bottom left; then clockwise, aged 15 months, 3 years and 5 years. Courtesy of Christopher and Jonathan Higgs.

Early academic career

Peter enrolled in 1947 as an undergraduate at King's College London. He graduated with a BSc in 1950, an MSc in 1951 and a PhD in 1954. He was awarded a Royal Commission of the Exhibition of 1851 Senior Studentship and spent that in 1953-54 at King's College and in 1954-55 at Edinburgh. The following year, he held a Senior Research Fellowship at Edinburgh before returning to London for a year as an ICI Research Fellow at UCL and a second year at Imperial College. Peter held a temporary Lectureship at UCL for two years from 1958.

Family photographs of Peter Higgs at his King's College graduation 1954 (upper) and with King's College students, courtesy of Christopher and Jonathan Higgs.

Edinburgh and the 'Gang of Four'

Peter came to Edinburgh in 1960 as a young lecturer, but was invited by Nick Kemmer to arrive early to take part in the first Scottish Universities Summer School in Physics at Newbattle Abbey in Dalkeith. A lecturer from the USA had had his fare paid by the National Science Foundation. The spare money was spent on wine for dinner and Peter was put in charge of it. Unbeknown to him, four students took wine from the table and hid it in the grandfather clock in the crypt.

'Gang of Four': Sheldon Glashow, Martinus Veltman, Nicola Cabibbo and Derek Robinson

(Glashow and Veltman were both future Nobel laureates, Cabibbo probably should have been, and Robinson was an axiomatic field theorist.)

Evading the Goldstone theorem

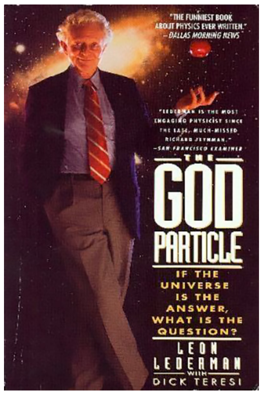
In 1960 Peter became interested in the work of Yoichiro Nambu that ran into a serious problem known as the Goldstone theorem. Peter's 1964 papers showed how to avoid that problem and introduced what was the precursor of the Higgs boson. In 1965 on sabbatical at the University of North Carolina he wrote a third paper, outlining the properties of this scalar boson, that was published in 1966.

All was quiet until Ben W Lee, gave a summary paper at the 1972 International Conference on High Energy Physics. Our colleague, Ken Peach, returning from the conference said that Ben had "put the name Higgs on everything" and told Peter in the University of Edinburgh Staff Club, "You are famous".

Peter and IT

Peter never used a computer, or a smartphone, and his allocated email address was monitored by departmental secretary Alvis Ingram, both before and after 1996 when he retired. When Alvis herself retired, I took over this task and as the search for the Higgs boson intensified, so did the corresponding email traffic.

The God Particle name arrives



There were often amusing and sometimes bizarre messages and stories. When Leon Lederman coined the term 'God Particle' in 1993 it led to yet another strand in the growing email traffic.

We were told in separate messages that the particle had been predicted much earlier by all the Holy Books, as well as more recently by Homer Simpson. Despite Peter despairing of this moniker, it has stuck around, particularly among journalists wishing to make headlines. We received a letter in Chinese addressed to Peter and I asked a colleague, Crystal Lei, to translated it. Crystal told me that it was about the Higgs boson. I pressed her further and she told me that the two Chinese characters for Higgs boson were literally 'God' and 'Particle'.

Higgsteria

The *New Scientist* coined the phrase 'Higgsteria' to describe not only the search for the boson, but the media attention around it. I set up an automatic Google News search for items including the phrase 'Higgs Boson' and got many hits every day and this persists even at the time of writing. I get hits from India of results for a racehorse and financial reports for a medical company, both with that name.

A newspaper cartoon appeared of three wise men on camels arriving at the CERN gate demanding to see the 'God particle'. A farmer in Aberdeenshire had a herd of bison one of which was called Higgs Bison. Headlines often were misspelled and called it the 'Higgs bosun'. Its discovery will be mentioned later! There was another more unfortunate misspelling. We received an email from a lady fresh out of her Tai-Chi class claiming, "I felt the fifth force" and then wished Peter well in his search for the 'Higgs bosom'. Help on that was on hand as we were sent a copy of the *Camden Review News Extra*, reporting that 'John Ellis, a Higgs Bosom expert, is a Highgate (School) old boy'. There were several

Higgs Boson ales brewed of which more later, and fine red wines produced in both California and France named ‘Higgs Boson’. Its name made it to the *Guardian* Crossword No. 24983 as the answer to the clue 17 across: ‘Gosh big’s no way to describe it, though it is important in theory (5,5).

CERN Open Days, April 2008

On the weekend of 5-6 April 2008, CERN planned an Open Day, ahead of the switch on of the Large Hadron Collider. In advance of that I tried to call Peter without success and then called his estranged wife Jody. I explained that I hoped Peter was up for the trip to CERN in April. Jody told me “Peter doesn’t like big machines, but I will ask him”. Jody then quietly told me “My cancer is back”. Peter called soon after and agreed to go, but sadly Jody passed away shortly afterwards. I waited for some weeks to pass until Peter called to ask, “Are we still going?”. He wanted it to be a ‘private’ visit, so I made all the arrangements directly with the spokespersons of the four large LHC collaborations. However, when we asked for CERN visitor permits, the office issuing them leaked the news that Peter Higgs was coming to CERN. This, of course really impacted on the nature of the visit.

The April trip to CERN included several colleagues from the University of Edinburgh. We flew out to Geneva on the Friday, and, with our hired minibus, we first visited CMS (Compact Muon Solenoid) as it was the furthest from the airport. Tejinder Virdee kindly showed us around and Peter passed a whiteboard where someone had written ‘There is no Higgs’.

When we in the car park preparing to leave, a group of students working on CMS came running towards us shouting “You can’t leave yet!” As they got closer, they held out their hard hats for Peter to sign! We eventually left and booked into our hotel.

There is no Higgs! Peter Higgs visiting the CMS experiment 4 April 200;8: © Peter Reid, University of Edinburgh

Higgs at ATLAS

Peter Higgs at the ATLAS Control Room 4 April 2008; © Peter Reid, University of Edinburgh

After checking in, we travelled to the ATLAS experiments where we were kindly shown around by Peter Jenni. Later in the ATLAS control room, Peter Jenni remarked that he hoped that they would see the Higgs boson at ATLAS first. I apologised to him and said, “I am afraid the Higgs has already been seen at CMS!”

Higgs at Alice

We visited the ALICE experiment on the following Saturday, which was the CERN Open Day for family and friends. I managed to take a photograph of Peter in the straight section of the tunnel next to the experiment, wearing the green ALICE hard hat.

Peter Higgs in the LHC tunnel near the ALICE experiment 6 April 2008; © Alan Walker, University of Edinburgh

We were invited afterwards for a beer at CERN Restaurant One, as a journalist wished to have a short interview with Peter. After two rounds of beers, it became clear we had been stationary for too long. Suddenly, a group of US students arrived with a camera and microphone which was thrust at Peter, with the cry “Say hello to America!” They had been at the Prévessin site, so news of Peter Higgs’s whereabouts was travelling fast. As we retreated, Richard Kenway remarked, “Now I know what it feels like when the paparazzi chase you!” We had learned our lesson! The following Sunday was CERN’s Open Day for the public, so we kept a lower profile and after a brief return to ATLAS we went downtown.

On the following Monday morning we visited LHCb (Large Hadron Collider beauty experiment) and the Edinburgh group working there showed us around. By now the Director-General Robert Aymar had learnt that Peter Higgs was visiting CERN, and he invited our group to lunch in the Restaurant One 'glasshouse' where Peter signed the 'Golden Book'. Clearly, trying to keep his visit private was never really going to be possible!

Peter Higgs signing the 'Golden Book' (with Robert Aymer, Director General of CERN), 7 April 2008; © Peter Reid, University of Edinburgh

On the Monday afternoon a University of Edinburgh press conference was held off campus. A French reporter asked if there was a picture of Peter in the LHC tunnel. I obliged, asking him to use it only for his story. He later complained, "They were treating him like a rock star". Well yes, by that time Peter really was the 'rock star of physics'.

Travels with Peter

From 2008, I was asked to help Peter with his travel to the many award ceremonies he attended, such as the Freedom of the Cities of Newcastle, his birthplace, and Bristol where he grew up. Peter remarked that the sole benefit from Bristol was that he could now graze his herd of sheep on Bristol common land. In Newcastle he opened a science park on the site of the former Federation Brewery, itself on the site of an old coal mine. This was in Elswick where Peter was born in a maternity home that we are yet to identify.

Honorary degrees

Peter had many honorary degrees awarded. One was awarded at the University of Manchester where he told me he sat chatting to the person next to him called Bobby Charlton, then said "I had no idea who he was". Peter was never interested in football or any other sport!

Erice, July 2012

Nino Zichichi, the Sicilian physicist, had invited Peter several times to go to conferences in Erice, near Palermo, but Peter sometimes did not turn up. Nino then invited Peter and me which seemed to fix that problem. Peter and I were together there in June 2012 and by then LHC had been running for several years and the data taken on the possible Higgs boson candidate events was growing. Before we left Edinburgh, I had asked James Gillies of the CERN Press Office if we should travel to CERN afterwards and was told that there would be no news in the summer, more likely in the winter. As a result, we booked to return from Palermo to Edinburgh via London Stansted. When we were in Erice we began to hear rumours. A former LHC experiment spokesperson had left early, and another had cancelled their visit. Jonathan Leake, a *Sunday Times* journalist, emailed me to ask if Peter was going to CERN. Then we heard that Gerry Guralnik and Carl Hagen had already arrived at CERN. Finally, Jan van den Berg, of the Ad Hoc Theatre Group in Amsterdam, phoned to say he had been filming in CERN and was coming to film Peter on the Saturday in Erice. With all this activity I sent an email enquiry to James Gillies to find out what was happening. Peter and I, and the film crew, adjourned to lunch to Ristorante Venus which had no Wi-Fi. During lunch my mobile phone rang, and I left the table and moved to the large window to take the call. I turned round to find the film crew filming me taking the call. It was in fact John Ellis, phoning me from Switzerland. John very strongly suggested that Peter should come to CERN. Peter was also filmed saying "If John Ellis says that, then we must go!" Later, back at the conference centre I picked up an email from James Gillies of the CERN Press Office which included the message "I can't give you details of what will be said on Wednesday, though I do suspect that Peter will regret it if he is not there."

Arrival in CERN, 2 July 2012

We discarded our return travel booking and I organised for the two of us to fly from Palermo to Geneva via Rome on Monday 2 July 2012. As we were extending our trip, Peter could not get through to extend his single-trip insurance, so he travelled without cover. We were picked up at Geneva Airport by the Director-General's car and taken to the CERN hostel where we booked into separate buildings. Making our way to our rooms, a young postgraduate kindly offered to carry Peter's bag. She asked Peter "Which experiment do you work on?" He was much amused, so I introduced her to Peter Higgs and there were smiles all round.

Peter and I met for a late dinner in CERN Restaurant One and the same young student smiled at us from her table. When we had almost finished our meal and we were drinking coffee, she came over and asked Peter to sign her laboratory notebook. Almost immediately a queue of about 50-60 formed at our table, all waiting for selfies and autographs. Peter kindly obliged most but was clearly very tired and I eventually had to interrupt and take him away.

CERN, 3 July 2012

The next day, Tuesday 3 July, we were protected by Jane Mackenzie, UK Liaison Officer at CERN. We had breakfast in the UK Liaison Office and Jane booked a lunch off campus. On the way, Peter was invited to meet a group of international school pupils but James Gillis intercepted us and gave Peter the press statement that would be released the next day after the seminar. Peter and I had lunch with a large group of University of Edinburgh colleagues. In the afternoon, he was taken for a filmed interview that would also be released after the seminar. As he sat down, he was asked "Have you read the press release?" Unfortunately, Peter had had no time to read it and so it was only then that he was made aware of what was to come the following day!

On that Tuesday evening, we were kindly invited for dinner by John Ellis at his home, along with former CERN Director-General Chris Llewellyn-Smith of the University of Oxford. We all shared a bottle of champagne, and the bottle is now held by the Science Museum in London.

The CERN Seminar, 4 July 2012

The day of the CERN special seminar, Wednesday 4 July 2012, was an incredible event for all, with students and others queueing overnight for a place. Apparently, a fire alarm was set off, but the queue refused to leave and the attending pompiers eventually gave up and let them stay. Jane Mackenzie took great care of us, and we had the use of a private room close to the auditorium. Security guards were outside to keep order, whilst Peter Higgs and I sat together, under the care of Jane Mackenzie.

The announcements of the results, by Fabiola Gianotti for ATLAS and Joe Incandela for CMS, were each met with standing ovations accompanied by whoops of delight the likes of which had never been seen before. As the seminar ended, Peter was asked by the Director-General, Rolf Dieter Heuer, if he had expected this discovery, Peter replied, "Well it had to be there, but I did not expect it to be found in my lifetime!" It was, after all, 48 years since his 1964 papers.

End of the CERN Seminar on 4 July 2012. Alan Walker (standing) and Peter Higgs (sitting) are in the third row on the right-hand side; © CERN

Peter had to be escorted as we moved from the auditorium to the following press conference room, as the media crowd filled the corridor, walking backwards as we advanced towards them. The camera and microphone operators filled the doorway. We were diverted and escorted in through a side door. At the end of the press conference, Peter was asked to comment, but he replied, "It is not for me to comment. This is the day for the experimentalists and what they have so magnificently achieved." That was a mark of Peter's respect for what many thousands had so successfully undertaken.

We had lunch afterwards in our private room near the auditorium where we talked to CMS colleagues, Joe Incandela and Ian Shipsey. Ian was a former Edinburgh postgraduate working on NA31. He became Head of Physics at Oxford University but sadly died far too young in September 2024. Later that afternoon, Jane Mackenzie led us to our car as we left for our EasyJet flight to Edinburgh. Jane suggested that we should celebrate with Prosecco on our flight back. Peter turned down Prosecco in favour of a beer and choose a can of Fuller's London Pride. The empty can was collected and is lost for good. I shared a half-bottle of Prosecco with a young female postgraduate from the University of Glasgow returning from CERN.

Edinburgh Press Conference, 6 July 2012

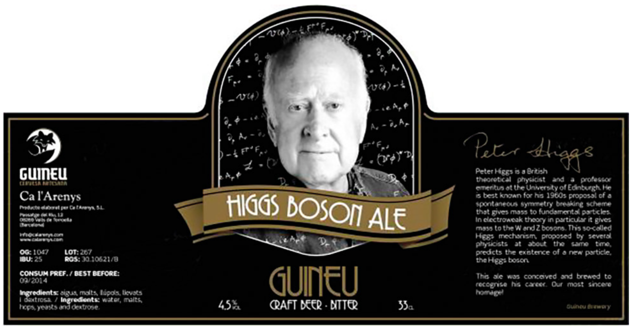
On Friday 6 July a press conference was held back in Edinburgh when it was announced that that a Higgs Centre for Theoretical Physics was to be established. When Peter was asked if he had celebrated with champagne after the seminar, he pointed out that he had chosen a beer. At that point I passed him a Fuller's London Pride which I had brought with me! We did all share champagne at the lunch afterwards!

RSE Exhibition 'From Maxwell to Higgs'

The Royal Society of Edinburgh was concerned that Peter might be awarded a Nobel prize in 2012 and commissioned myself and David Saxon of the University of Glasgow to write and design a 13-panel exhibition for the Upper Gallery in their headquarters in George Street Edinburgh. The resultant 'From Maxwell to Higgs' was officially opened by RSE Patron, the Duke of Edinburgh, on 26 September 2012. He was shown round the exhibition and, despite his equerry urging him to leave, he persisted in seeing all the panels. A copy of the exhibition is in the James Clerk Maxwell Buildings at the University of Edinburgh.

The First 'Audience with Peter Higgs'

Peter was now in great demand for interviews and comments. A student society, the Edinburgh University Young Student Researchers Association (EUYRSA) asked if Peter would give a lecture, and this resulted in an 'Audience with Peter Higgs'. This turned into a talk shared by Peter Higgs and me, along with Victoria Martin and Francesca Garay Walls. Peter had been involved in my appointment; we had both lectured to Victoria as an undergraduate and Victoria had mentored Francesca, who was from Chile, on the ATLAS experiment. As a result, the subtitle of the lecture was 'Four generations of particle physicists. The EUYRSA event, held on 30 October 2012, was so overwhelmed that it had to be moved from a lecture theatre holding 150 to one that held 350! This was the beginning of a series of such events.



Label from the Guineau Brewery 'Higgs Boson Ale';
© Xavier Serra 2012

Cosmo Caixa, Barcelona 6 November 2012

In Barcelona on 6 November 2012, we held a repeat 'Audience with Peter Higgs' in the Cosmo Caixa science centre, which held 300. The event was streamed in English, Spanish and Catalan to a virtual audience of 5000. At the end of the lecture Xavier Serra, of the Guineu craft brewery, appeared clinking newly bottled and labelled Higgs Boson ale. The next day we were hosted for lunch at a tapas and craft beer bar. The people involved became good friends and later joined Peter in Oviedo in Spain in October 2013 and travelled to Plockton in Scotland in April 2014.

New Year Honours List 2012

On 26 December 2012, in the British New Years Honours list, Peter Higgs was made a Companion of Honour, and I was awarded an MBE. Peter delayed his investiture at the Palace of Holyroodhouse in Edinburgh until the July 2014, as he had promised Nino Zichichi that he would travel to Erice in July 2013.

Nonino 2012 Prize 'Man of Our Time'

There were memorable trips with Peter to Nobel-like prize ceremonies, one of them in northern Italy. On 26 January 2013, the 2012 Nonino Prize ceremony was held in the Nonino family's grappa factory in Ronchi di Percoto, where Peter was given the Nonino award of 'The Man of Our Time'. The Nonino family certainly know how to host a party in a distillery! The family kept in touch with Peter and sent annual presents of their exclusive grappas.

More Audiences with Peter Higgs

Between 2 May and 7 May 2013, the 'Audience with Peter Higgs' went on an extended trip to Ireland, presenting to about 80 at the Royal Irish Academy in Dublin, to 200 at Maynooth University and to about 150 at Queen's University Belfast. On 20 June 2013 the largest 'Audience with Peter Higgs' was presented by the original speakers at the McEwan Hall, Edinburgh, full to its capacity of 900.

Erice, June 2013

On 28 June 2013, Peter and I set off for Erice, flying from Edinburgh to Palermo via Paris and Rome. On arrival at Rome, as we disembarked, we were surprised to be met by a limousine and were given VIP treatment. Our passports were collected, for our onward travel to Palermo to be taken care of. We entered the airport via a side door and were deposited in an Alitalia VIP lounge where we relaxed. As time passed, we became somewhat concerned and our minder returned with our passports in hand, ushering us quickly back to the door we had entered. Unfortunately, things then began to get chaotic. There was a carabiniere at the door, who refused to allow us to leave through it. Our minder became agitated and wandered around the room waving the passports in the air and speaking on his mobile phone. He ignored our pleas to give us our passports and take us to our gate. After a considerable time, he told us we had to do just that. He dropped us off at the gate and promptly disappeared. It became clear that the passengers boarding in front of us had taken our seats and we had missed our flight. Worse was to follow as the next two flights were full, and we ended up being allocated seats on the last flight to Palermo. The VIP lounge closed shortly afterwards, and we were asked to leave. We did eventually get to Palermo that evening, but no thanks to the VIP treatment. No-one admitted blame for this chaos!

Prince of Asturias Awards, Oviedo October 2013

In Oviedo in October 2013, for the Prince of Asturias Awards, Peter's guests included Jane Mackenzie, friends from Cosmo Caixa and friends from the Guineu craft brewery. This group became known as 'Team Higgs Oviedo'. We stayed in the same hotel as Prince Felipe and his wife Letizia. They were extremely warm and friendly, and we shared several jokes. On Peter's death in April 2024, as the King and Queen of Spain, they sent to Peter's family a very generous memorial tribute.

Nobel Announcement, 8 October 2013: Where's Peter?

Peter had not expected a Nobel award in 2012 as he thought that would already have been decided. However, he expected that it might be made on 8 October 2013, and he decided he did not wish the media attention that would follow. He planned to be on his favoured West Coast of Scotland at a place he would not divulge. A team of colleagues in the School of Physics and Astronomy at Edinburgh were tasked to staff several phones. Many of us gathered in the Higgs Centre for Theoretical Physics to watch the announcement and this was much delayed. Immediately it was announced that Peter was sharing the Nobel Prize in Physics 2013 with François Englert we left to staff the phones. The team took many enquiries and gave phone interviews. Some of us had to break off and do filmed interviews for television news channels. By 5 pm we had to call it a day and adjourned to celebrate at a local inn. I was collected by my brother John who was visiting and arrived back home to celebrate with my wife Catherine and sister-in-law Betty who were already celebrating. Catherine later answered the phone and exclaimed "Peter, where are you?". Peter apparently replied, "I am at home of course". It transpired that Peter had been unable to drive as his car had lain unused for six months and would not start. He thought of travelling away by train, but that was not going to work out. Instead. Peter had left home, before the announcement had been expected, to a newish restaurant/bar, The Vintage, that served nice seafood and craft ales in Leith. He returned home on foot, taking in an exhibition at a local art gallery. He was nearing home on Heriot Row when a car squealed to a sudden halt and an ex-neighbour got out and shouted "Peter, my daughter called me from London. Congratulations on your award!" Peter told me that his replied was "What award". The Higgs was once again found!

Preparing for Stockholm

The Nobel announcement, on 8 October 2013, set in motion the arrangements for Stockholm later in the year. I was contacted by Peter's Nobel Attendant, Ola Pihil, and he and I made most of the arrangements, including such detail as his measurements for his Nobel attire and the menu for his Nobel guests' lunch in the Grand Hotel Stockholm. Peter kindly invited as one of his guests, Kathleen Graham, Robert Brout's widow.

A 'Massive' mistake

Ahead of travelling to Stockholm I read the paper on the Nobel website 'Scientific Background on the Nobel Prize in Physics 2013' which showed the equation of motion of the leftover scalar boson. This first release described this as that of a 'massless scalar' which it clearly was not. Lars Brink replied that this had been proof-read many times and had not been picked up. In the final release this 'massive' mistake disappeared.

Collider exhibition, 12 November 2013

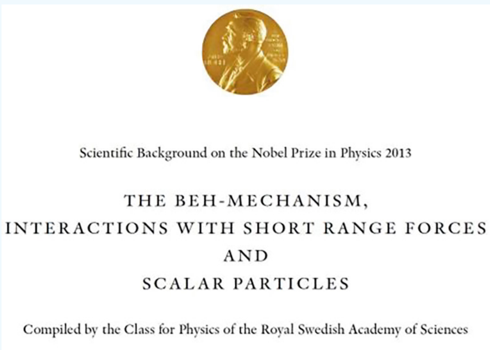
On 12 November 2013, Peter and I were guests at the opening of the London Science Museum's particle physics exhibition 'Collider'. We discovered that Fuller's of Chiswick had picked up on earlier news and donated a large batch of their London Pride ale labelled 'Professor Peter Higgs, Nobel Prize Winner 2013".

Awards for a 'Gang of three'

On 28 November 2013, there was an extraordinary University graduation ceremony. The Royal Society of Edinburgh presented Tom Kibble with its Royal Medal; François Englert was awarded a University of Edinburgh honorary degree and Peter Higgs was awarded an honorary degree from the Free University of Brussels.

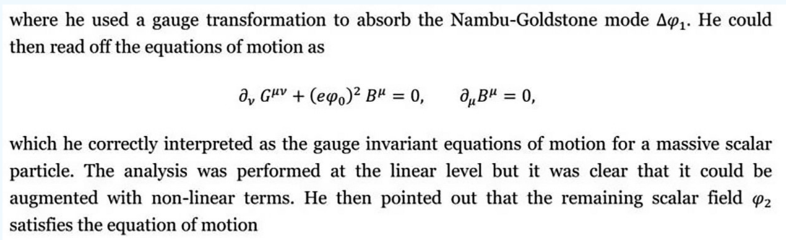
The journey to Stockholm

The journey to Stockholm proved to be hectic. Peter turned down an invitation to visit 10 Downing Street, as his schedule was already full. Peter and I had to travel first to London on 4 December 2013, to attend a special lunch for British Nobel laureates at the Swedish Ambassador's residence. From there we took a taxi to our hotel where Peter was immediately upgraded to a VIP suite, so we became separated in the hotel. Peter was interviewed that afternoon by a national newspaper. As the journalist and crew had avoided travelling to Edinburgh, we cut a deal that they would take us to dinner. That turned out to be a continuation of the interview as the dinner conversation was recorded! The following morning, we were to travel to the BBC studios for Peter to be interviewed by Jim Al-Khalili for his programme 'The Life Scientific'. I could not find Peter at breakfast. When I went to reception, a taxi driver appeared saying he was to take just myself to go to the BBC. When I finally arrived at the BBC, I was asked where Peter was. It turned out that Peter had been taken to the VIP breakfast room which I was not allowed into. This was yet another time that VIP treatment was to cause chaos and upset carefully prepared plans. A taxi had to be sent to retrieve Peter. During his interview, Jim asked Peter "Can you explain the Higgs boson in one sentence?". Peter looked aghast and simply said "No". I think this is why Jim, when asked later what his worst interview was, he said it was with Peter Higgs. Much later Jim, when asked what his best interview was, gave the exact same response! We rushed to our taxi and took the Heathrow Express to catch our flight to Stockholm. This would be the start of a very busy Nobel Week.


Scientific Background on the Nobel Prize in Physics 2013

THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES

Compiled by the Class for Physics of the Royal Swedish Academy of Sciences


where he used a gauge transformation to absorb the Nambu-Goldstone mode $\Delta\varphi_1$. He could then read off the equations of motion as

$$\partial_\nu G^{\mu\nu} + (e\varphi_0)^2 B^\mu = 0, \qquad \partial_\mu B^\mu = 0,$$

which he correctly interpreted as the gauge invariant equations of motion for a massive scalar particle. The analysis was performed at the linear level but it was clear that it could be augmented with non-linear terms. He then pointed out that the remaining scalar field φ_2 satisfies the equation of motion

The extract where 'massive' replaces the original massless

Peter's Nobel Lecture, 8 December 2013

Peter's Nobel lecture on 8 December 'Evading the Goldstone Theorem' included the 1960 tale of the grandfather clock. In the audience was the British Ambassador to Sweden and his wife. The following day we were lunch guests at the Ambassador's residence in Stockholm. At the end of lunch, Peter was invited to take part in a small ceremony and was taken into the hallway. Behind him was a grandfather clock and he was asked to open it and reach in. So, 53 years later, a re-enactment took place!

The British Ambassador to Sweden, his wife, Michael Leavitt and, on the right, Peter Higgs (with wine from the long-case clock); © British Embassy in Stockholm

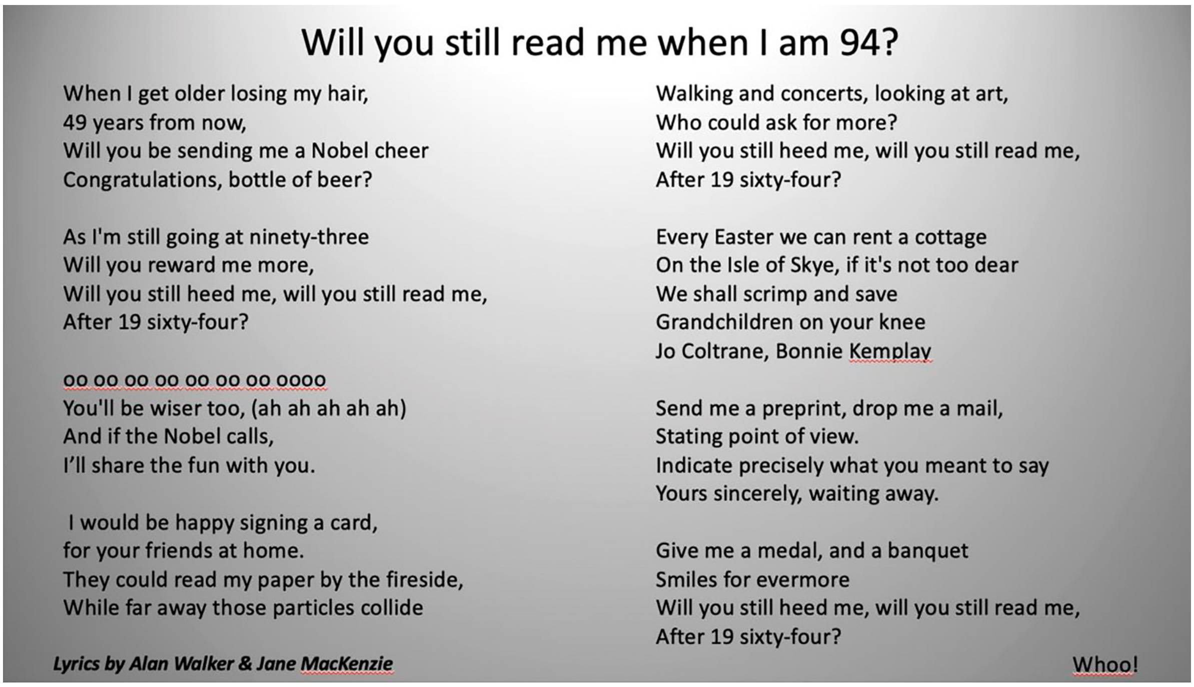
© New York Times

The Nobel Ceremony, 10 December 2013

For the Nobel awards ceremony on 10 December, Peter and his male guests were all fitted with the official Nobel formal attire. It was probably best described as 'Downton Abbey dinner attire'. The Nobel laureates were provided with patent leather shoes which proved uncomfortable. Peter joined with François Englert in breaking the Nobel rules, but they got away with it. My brother John watching television texted me to say he could see my wife Catherine sitting next to her butler! At the Nobel banquet that evening I was sitting next to Tejinder and Vatsala Virdee. Vatsala asked me in conversation "Do you watch Downton Abbey?" I looked down at my formal attire and smilingly said "Quite frankly my dear, I think I am in it".

A song for Peter

After the Nobel banquet Peter retired to the Grand Hotel, whilst some of us took up the invitation for the traditional party at the Karolinska Institute. Jane Mackenzie and I had written new lyrics to the Beatles song 'When I'm 64'. Ola had arranged for a local a capella group to sing this. Sadly, Peter missed it.



© Alan Walker & Jane Mackenzie, with thanks to the Beatles

Nobel Reception at Nordic Museum 9 December 2013; © Nobel Foundation

Nobel week remembered

Nobel week was full of lunches, dinners, concerts, meetings and receptions. There was a gathering at the Nordic Museum, full of Nobel guests and school children (next page). A crowd gathered around Peter, with one student asking the often-asked question "How do you get a Nobel Prize". Peter's answer was always inspiring but always ended with the same phrase. By then I knew what was coming and told those at the rear of the group that he would say "but then you need to get lucky". When he did, they all turned to me and laughed and then applauded him.

The Plockton gathering, 18-22 April 2014

At the Easter weekend of 18-22 April 2014, the last of the talks 'An Audience with Peter Higgs' took place in Plockton, near the Isle of Skye in Scotland. It was given to a general audience in the village hall on Easter Sunday and then on Easter Monday to Plockton High School with senior pupils travelling from Portree, Wick and Inverness. We were house guests of Jane Mackenzie who was by now a great friend. We were joined by our Spanish friends from Barcelona, so Team Higgs Oviedo became 'Team Higgs Plockton'. They brought with them another batch of Higgs Boson ale with the label jokingly announcing that it was from the Higgs & Walker Brewing Company. The local Plockton pub had on tap a special 'Partic Ale' celebrating that Peter Higgs was in town. Peter had already been out in a local fishing boat, where a photograph captured him at its wheel. The 'Higgs Bosun' was found that weekend in Plockton.

Honorary degree and the Higgs blue plaque

In 2015, Peter was awarded an Honorary Degree in Edinburgh by the University of North Carolina at Chapel Hill where he had written his longer paper on the properties of the scalar boson that was published in 1966. Afterwards an Institute of Physics blue plaque was unveiled outside the building in which he had written his two 1964 papers.

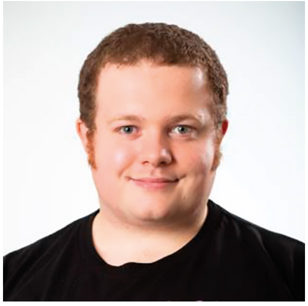
IOP plaque unveiling at 5 Roxburgh Street, Edinburgh;
© University of Edinburgh

The story of Conor Ransome

Over the years, we were used to large numbers of mail and email requests for Peter's signature and signed photographs. There was one such request which stands out. So, I would like to share a story that could only have happened through

Courtesy of Jane Mackenzie, Plockton

my association with Peter and the opportunities that flowed from that.



Conor Ransome

One evening, at home in Edinburgh, I received, on behalf of Peter, a text from Deborah Ransome in Doncaster, which is close to my own birthplace in South Yorkshire. Debbie's iPad message asked Peter if he would sign a 21st birthday card for her son Conor who was an undergraduate at the University of Durham, taking a degree in physics and astronomy. What was extraordinary about this message was that Debbie went on to say that "Conor was not expected to live beyond the age of 12 months as he had a very rare genetic disorder". I was told later that this was chondrodysplasia punctata. My late wife Catherine immediately volunteered to buy a card and Peter agreed to sign it. However, this request came just before my trip with Peter to Oviedo, where François Englert would be present. I emailed Rolf Dieter Heuer and asked if he could arrange a VIP CERN visit for Conor and family. The card was duly signed by Peter, François and Rolf ahead of Conor's birthday on 3 November 2013. Peter had been invited to share the University of Durham annual Collingwood lecture on 5 November 2013. Professors Nigel Glover and Anne Taormina who were organising this event, agreed to invite Conor to the lecture. Meanwhile, I suggested to Debbie and her husband Sheldon that they should also attend. Reserved places were set up so they could sit together. Conor, who knew nothing of these arrangements, was surprised to meet his parents in the queue! At the end of the lecture Carlos Frenk, who was chairing the lecture, announced that Peter had a card for someone who had had a recent birthday and Peter duly presented the card to Conor. At the same time, I placed on the document projector the letter, signed by Rolf Heuer, inviting Conor and his family for their VIP visit to CERN. Conor's surprise went down very well with the audience. After the lecture, I met again Debbie and Sheldon and then met Conor for the first time. It was only then that I fully understood the extent of his disabilities and the operations that he had survived in his childhood. Debbie, Conor and his younger brother Finn did indeed have their VIP visit to CERN, whilst Sheldon stayed at home to care for daughter Niamh. Due to illness, I could not join them, but I have stayed in touch with the family ever since. In 2022 Conor completed a PhD in astrophysics at Liverpool John Moores University, spending time at the Isaac Newton telescope in the Canary Islands. He was a postdoctoral scholar at Pennsylvania State University and since August 2023 he has been a postdoctoral fellow at the Harvard & Smithsonian Center for Astrophysics. I have enormous admiration for both Conor and his wonderful family. It was my extremely good fortune to have known Peter Higgs, and it is that association that created this wonderful opportunity and the resultant friendship.

Remembering Peter

During our many years of travels together, I got to know Peter very well. He had fantastic recall and great depth of knowledge on many subjects. He was always modest and very kind to all, especially younger people. His passing was very sad, but we should all remember him for the person he was. He will be missed by many. I remain good friends with his family, and it was both an extraordinary privilege and pleasure to know him. It would seem to me that I did indeed get exceedingly lucky!

Appendix

For those unfamiliar with the Higgs boson, the Editors recommend the following popular science books, downloadable articles and exhibition.

Books

Sample, I., *Massive: The Higgs Boson and the Greatest Hunt in Science*, updated edition, Virgin Books, 2013.

Butterworth, J., *Smashing Physics: Inside the World's Biggest Experiment*, John Murray, 2015.

Also:

Close, F. *Elusive: How Peter Higgs Solved the Mystery of Mass*, Penguin, 2023.

Gillies, J. *CERN and the Higgs Boson: the Global Quest for the Building Blocks of Reality*, Icon Books, 2018.

Carroll, S. *The Particle at the End of the Universe*, Dutton, 2012 and Oneworld Publications, 2019.

Randall, L. *Higgs Discovery: the Power of Empty Space*, Bodley Head, 2012.

Free articles

'The scientific discovery of the Higgs Boson at the LHC', by Peter Jenni and Tejinder S. Virdee, at https://cds.cern.ch/record/2743162/files/Jenni-Virdee2020_Chapter_TheDiscoveryOfTheHiggsBosonAtT.pdf

'Here at last!' (Royal Swedish Academy of Sciences) at www.nobelprize.org/uploads/2018/06/popular-physicsprize2013-1.pdf

'A layperson's guide to the Higgs Boson', by Victoria Martin, at www.ph.ed.ac.uk/higgs/laypersons-guide

Exhibition

For several years the exhibition, *From Maxwell to Higgs*, by Alan Walker and David Saxon was displayed in the Upper Gallery at the Royal Society of Edinburgh. There is a copy hanging in the James Clerk Maxwell Building of the University of Edinburgh.

Author: Dr Alan Walker, Treasurer and former Chair of the James Clerk Maxwell Foundation

THE BIRTH OF THE CAVENDISH LABORATORY

By *Malcolm Longair*

The opening of the Cavendish Laboratory in 1874 was the result of a long campaign to make experimental physics an integral part of research and teaching at Cambridge University. From the beginning of the 19th century, the emerging sciences of electricity, magnetism, heat and thermodynamics were added to the edifice of Newtonian physics and found practical application in the burgeoning industrial revolution.

The entrance to the Cavendish Laboratory on Free School Lane

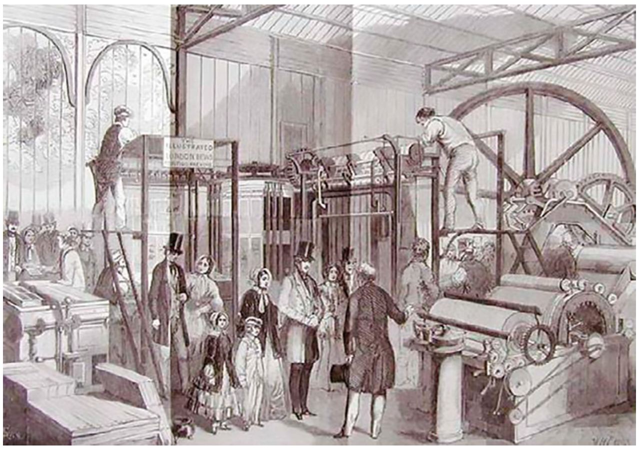
Experimental physics in Britain was largely carried out in private laboratories or workshops but was not part of university curricula. In Cambridge, natural philosophy was at a rather low ebb. As Edmund Whittaker wrote:

> 'The century which elapsed between the death of Newton (1727) and the scientific activity of [George] Green (1841) was the darkest in the history of [Cambridge] University. … In the entire period the only natural philosopher of distinction was John Michell … but his researches seem to have attracted little or no attention among his collegiate contemporaries and successors, who silently acquiesced when his discoveries were attributed to others.'

In 1841, Albert, the Prince Consort, took on the role of promoting industry and science in Britain. His most spectacular achievement was undoubtedly the Great Exhibition of 1851, intended to demonstrate that the country was an industrial leader on the global stage.

Well before this time, however, Albert had been convinced of the need for the reform of Cambridge University. He became Chancellor of Cambridge University and proposed a number of reforms in 1848. The general consensus was that the University had fallen behind in the fields of the physical sciences. The proposals were generally welcomed but faced opposition from more conservative elements, which can be gauged from the response of William Whewell, Master of Trinity College:

> '… mathematical knowledge is entitled to paramount consideration, because it is conversant with indisputable truths … that such departments of science as Chemistry are not proper subject of academic instruction …'



Queen Victoria and Prince Albert visit the machinery department of the Great Exhibition of 1851. (Courtesy of the Special Collections Department, Library, University of Glasgow)

But the Prince had allies. The prime minister Lord John Russell appointed a Royal Commission in 1848 to investigate 'the State, Discipline, Studies and Revenues of the University of Cambridge'. The Commission's report confirmed the Prince's recommendations, remarking that

> 'the operation of social causes little within [the University's] control left out of her true position, and become imperfectly adapted to the present wants of the country, so as to stand in need of external help to bring about some useful reforms.

Despite Whewell and the conservatives' opposition, the Commission stuck to its guns, recommending that there should be a 'complete and thoroughly equipped laboratory for chemistry …' Were the recommendations accepted, there did not appear to be any reason 'why Cambridge should not become as great a School of physical and experimental as it is already of mathematical and classical instruction.' An immediate result was the establishment of the Natural Sciences Tripos in 1851, including chemistry, mineralogy, geology, comparative anatomy, physiology and botany, but physics was not included. It was only treated as a distinct discipline in 1861.

The importance of physics for industry was brought home by the involvement of William Thomson, the future Lord Kelvin, in laying the first successful transatlantic cable. The first attempt by the Atlantic Telegraph Company, costing £350,000, had proved to be a disaster – the cable deteriorated rapidly and was unusable in a matter of weeks. Thomson had already made a study of such cables using electromagnetic theory, but his results were rejected by the empirical electricians. A further £1 million was raised and, following Thomson's recommendations, a cable was successfully laid in 1866. Thomson was knighted in the same year, an unusual distinction for a university professor. The University of Glasgow provided him with a suite of six experimental laboratories in their new buildings.

The untimely death of the Prince Consort in 1861 threatened to delay the Royal Commission's reforms. He was succeeded as Chancellor by William Cavendish, who became the seventh Duke of Devonshire in 1858. Cavendish, a distant relative of the famous natural philosopher Henry Cavendish, was a first-rate scientist. He excelled in the Mathematical Tripos and was the first Smith's Prizeman in 1829. He was also a major investor in the steel industry, applying scientific methods to improve industrial steelmaking. The discovery of rich deposits of high-grade haematite ore on his estates in north Lancashire resulted in a vast expansion of steelmaking capacity. By his death in 1891, he had amassed a fortune of £1,790,870.

William Cavendish (1808–1891), 7th Duke of Devonshire, Chancellor of Cambridge University (1861–1891). Oil painting after George Frederic Watts by Katherine Maude Humphrey.

Britain was seriously lagging behind continental Europe in training in the physical sciences and engineering. Experimental physics was still not part of the Natural Sciences Tripos and so a further syndicate was appointed in 1868 to address the issue. It recommended setting up a professorship of experimental physics, as well as the construction of a specially designed laboratory. The professor would be supported by a demonstrator to give personal instruction to the students and a museum and lecture room attendant to service the laboratories, the instruments and apparatus. The cost of the building was estimated to be £5,000 and the instruments £1,300, while the annual cost of employing the professor, the demonstrator and the lecture attendant was £660.

The colleges, however, were not prepared to make the funds available. The deadlock was broken when Cavendish wrote to the Vice-Chancellor on the 10th October 1870,

> 'I am desirous to assist the University in carrying out this recommendation into effect, and shall accordingly be prepared to provide the funds required for the building and apparatus, so soon as the University shall have in other respects completed its arrangements for teaching Experimental Physics, and shall have approved the plan of the building.'

On 9 February 1871, the Council of the Senate agreed to accept the Chancellor's gift and to fund the posts needed to staff the laboratory. Finally in 1873, experimental physics was incorporated into the Natural Sciences Tripos.

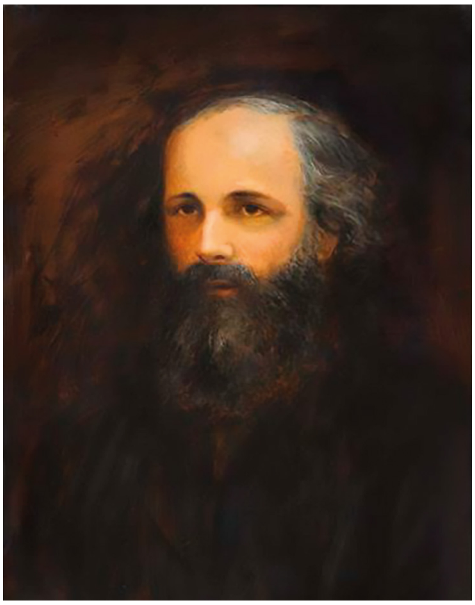
The electors to the Cavendish Professorship sought the best possible candidate for the new chair. An obvious choice was William Thomson, the most distinguished British physicist of his day, but with his well-furnished new laboratory in Glasgow and his industrial and domestic arrangements in the area, he was unwilling to accept the offer.

The electors turned to James Clerk Maxwell. His health had always been somewhat fragile and he had resigned his chair at King's College, London in 1865, returning to manage his family estate at Glenlair in Scotland, where he set about writing his monumental *Treatise on Electricity and Magnetism* (1873). In 1871, John William Strutt, who was to become the third Lord Rayleigh, wrote to Maxwell from Cambridge:

> '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 of experimenting, and who might direct the energies of the younger Fellows and bachelors into a proper channel ... I hope you may be induced to come; if not, I don't know who it is to be.'

Maxwell was ideally matched to the requirements of the professorship. As soon as his appointment was approved in 1871, he set about designing a state-of-the-art laboratory, visiting Thomson's lab in Glasgow and the Clarendon Laboratory in Oxford for inspiration. The site on Free School Lane was selected, which was sufficiently far from the main thoroughfares to minimise traffic vibrations. Plans drawn up by the architect William Fawcett were scrutinised by Maxwell, who altered the locations of walls and the disposition of the rooms according to his perceived needs. The cost of the building increased to £8,450, but Cavendish agreed to cover the shortfall.

Fawcett's plan for the ground floor of Cavendish Laboratory with Maxwell's changes indicated in his own hand in red pencil.



James Clerk Maxwell (1831–1879);
Oil painting by Jemima Blackburn.

The formal opening of the splendid three-floor building took place on 16 June 1874. On the ground floor, the highest stability was needed in the magnetism room. On the first floor, a large room for use by students contained ten tables, each containing a standpipe to which four Bunsen burners could be attached. The professor's private room had two hatches opening onto the students' laboratory, so that he could keep an eye on what they were doing. The lecture room had steeply raking seats for up to 180 students who could clearly observe the experiments being carried out on the long oak bench. Water was laid on in all the rooms. The height of the building allowed the construction of a Bunsen water pump with 'a vertical fall of considerably more than 50 ft ... used to exhaust a large receiver, from which pipes will communicate with the different rooms'.

Maxwell acquired an extensive suite of instruments funded by Cavendish's gift, as well as instruments he brought with him. Research activities got off to an encouraging start. Maxwell wrote to his uncle Robert Cay on 12 May 1874,

> 'The Cavendish Laboratory is now open to students for practical work, and several good bits of work are being done already by the men. I expect some of them will have matter for publishing before long.'

Ten physics laboratories were founded in the period 1866 to 1874 in 'British Institutes of higher learning' but most of the new laboratory directors struggled to maintain their research output in the face of heavy teaching loads and underfunding. Maxwell, however, took full advantage of the collegiate structure at Cambridge. The normal route for students joining the Cavendish was to complete their studies in mathematics and then proceed to experimental research under Maxwell's direction. They therefore had the mathematical skills to appreciate the most advanced problems in theoretical and experimental physics. Because of their success in the Mathematical Tripos, they would often win college fellowships or posts which enabled them to carry out substantial long-term research investigations.

The general view from outside was that Cambridge was too conservative to make a success of experimental physics. As Norman Lockyer, the influential founding editor of *Nature* remarked in 1874,

> '... it may take Cambridge thirty or forty years to reach the level of a second-rate German university in physical research.'

Lockyer had reckoned without the almost unique qualities of Maxwell, who set forth his agenda in his inaugural lecture in October 1871,

> 'The characteristics 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 be left to men of science will be to carry on these measurements to another place of decimals.'

Maxwell immediately rejected this view,

> '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 be poured... the history of science shews that even during that phase of her progress in which she devotes herself to improving the accuracy of the numerical measurement... she is preparing the materials for the subjugation of new regions, which would have remained unknown if she had contented with the rough guide of her early pioneers.'

Within ten years the laboratory was operating at the frontiers of experimental physics. Sadly, Maxwell died in 1879, but he had laid the foundations for what would prove to be 150 years of scientific discovery.

Acknowledgement

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Author: Malcolm Longair, Emeritus Jacksonian Professor of Natural Philosophy of the University of Cambridge, and Head of the Cavendish Laboratory (1997–2005)

POINCARÉ ON MAXWELL

By *Jeremy Gray*

Henri Poincaré (1854–1912) was a French mathematician, theoretical physicist, engineer and philosopher of science. He often discussed the work of Maxwell in his book *Électricité et Optique*. Here we explore some of his insights about Maxwell's theory of electromagnetism, starting with the title (Note 1). What links electricity to optics, the theory of light? This was one of Maxwell's discoveries, that electricity and magnetism may explain the nature of light, making it an electromagnetic phenomenon. More precisely and interestingly, he wrote (*Treatise*, Vol. 2, Ch. XX) that he had already attempted to explain electromagnetic phenomena by means of a mechanical action between bodies that assumes the existence of a medium between them (Note 2). The wave theory of light also assumes the existence of a medium, so it is required to show that the properties of these two media are the same, and in this way (see p. 431) "the evidence for the physical existence of the medium will be considerably strengthened." This would be the case if electromagnetic phenomena and light could be shown to travel at the same speed in all transparent media. Maxwell listed several determinations of these speeds, and observed that they are of the same order of magnitude, but none were yet determined with sufficient accuracy.

It is the shift from mechanical theories of points subject to ordinary differential equations, to a field theory, with its attendant partial differential equations, that has ever since been regarded as Maxwell's most significant contribution to physics. That said, his ideas about the nature of electricity caused nothing but trouble for even the greatest of his successors, as we shall now see.

The idea that electro-magnetic phenomena and light travel at the same speed was confirmed by Hertz in a careful and difficult experiment in 1888. This triggered Continental interest in Maxwell's theory, and Poincaré's attempt in his *Électricité et Optique* was the first book-length response. But Continental physicists found Maxwell's intuitions about the nature of electricity so different from their own that they failed to grasp the theory in its entirety, occupied as they were with theories about the flow of one or two electric fluids. Hertz famously said that the only part of Maxwell's work that he understood was the equations. (Nor, we should note, were they written in the neat form we find them in text books today, that was largely the achievement of Oliver Heaviside, but that's another story.) Instead, almost all of them rederived Maxwell's equations as a limiting case of Helmholtz's account in 1870, although this completely glosses over the fundamental difference between Maxwell's theory and Continental ones. On the Continent, electricity was regarded as a genuine substance, much as we do today. In Maxwell's theory, electricity is an epiphenomenon, and his ideas about the nature of electricity were, and remain, obscure, none more so than his ideas of charge and current.

Maxwell considered there was an infinite space that existed everywhere, even in places occupied by matter, to which he assigned a variable vector field with zero divergence, **J**. He supposed that this may be considered as the rate of flow per unit area of some conserved quantity, here denoted by the vector λ (see Note 3). A shift in location of this quantity may be written as

$$J = \frac{\partial \lambda}{\partial t}.$$

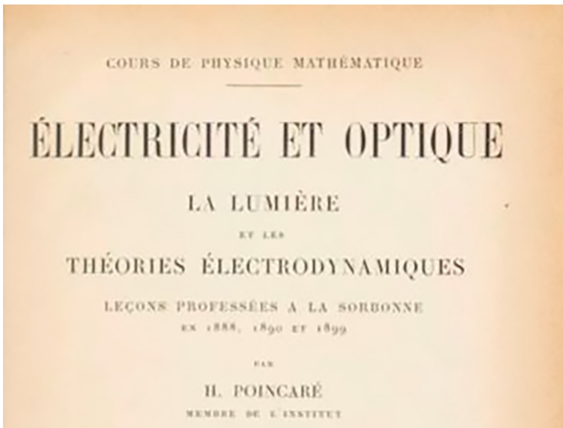
But this shift is not to be understood as a shift in some substance of which **J** is made, a claim that was to prove almost impossible for Continental physicists to get their minds around. It is a change in a *field*, which has discontinuities at the boundary of two different dielectrics, such as copper and air. Moreover, for Maxwell, every medium is a dielectric, even the ones normally considered to be conductors, and they differ only in their degree of readiness to conduct electricity.

Maxwell then introduced the concept of a displacement vector, **D**, somehow associated to λ but not identical with it; in fact, **D** may vanish without λ doing so. Consider now a conducting body containing a certain amount of electricity and bounded by a surface outside of which there is a dielectric medium. In Maxwell's theory, charge emerges as a discontinuity in the displacement vector due entirely to an alteration in conductivity at the boundary, and it resides entirely on the boundary.

What then is electric current in Maxwell's theory, if it is not the flow of some charge-carrying microscopic bodies? Understanding this is even harder, although the theory gets off to a simple start: current is simply **J**. If **J** is non-zero, Maxwellian theory says there is a current and a magnetic field **H** such that $\nabla \times H = J$. When we introduce a change in λ, say by bringing in a magnet, charge will change on the interface (this is polarisation), and a new equilibrium must be found for the energy in the conducting body and the surrounding medium. Some of this energy is dissipated as heat, and the rate of decay of this polarisation depends on the medium: it is extremely fast in copper and very slow, for example, in glass. For Maxwell, a conduction current is an extremely rapid change in the charge on the common boundary of the two media.

When Poincaré took up the subject in the late 1880s, he was better known for his work on pure mathematics (non-Euclidean geometry and what are today called automorphic functions), and for his work on dynamics and the global theory of differential equations (Note 4). However, he was never a Professor of mathematics, despite his reputation today. At the time, he was a Professor of mathematical physics and probability at the Faculté des Sciences in Paris. Unfortunately for us, Poincaré was not one for writing letters, except as replies to the many questions he was sent, and so we know nothing about why he decided to take up the study of electricity and optics. The book itself is described as lectures given at the Sorbonne in 1888, 1889, and 1890, and Poincaré as a member of the Institut de France.

Henri Poincaré in 1887
(by Eugène Pirou, via Wikimedia Commons)



COURS DE PHYSIQUE MATHÉMATIQUE

ÉLECTRICITÉ ET OPTIQUE

LA LUMIÈRE

ET LES

THÉORIES ÉLECTRODYNAMIQUES

LEÇONS PROFESSÉES A LA SORBONNE
EN 1888, 1890 ET 1899

PAR

H. POINCARÉ
MEMBRE DE L'INSTITUT

Upper part of the title page of *Électricité et Optique*

The first mention Poincaré makes of Maxwell in *Électricité et Optique* is in Chapter II, entitled 'Maxwell's theory of electric displacement'. He remarks correctly that Maxwell's theory emphasises dielectrics, which are filled with a hypothetical elastic fluid, analogous to the ether, and which he calls electricity. Poincaré thought this introduced a regrettable confusion in the mind, and he renamed it on p. 14 as "the inductive fluid" (fluide inducteur) of the hypothetical fluid, "conserving the usual meaning of the word *electricity*". Already, Poincaré has departed from Maxwell's ideas. He immediately went further, now he had a (hypothetical) fluid to talk about, and called a displacement of a molecule of the electric fluid an electric displacement. Indeed, Poincaré promptly claimed that simple mathematics forced the conclusion that the inductive fluid and electricity can be regarded as two incompressible fluids.

For Poincaré, there are two types of current, those flowing in closed circuits, which are usually permanent, and those flowing in open circuits, which are usually instantaneous (such as occur when a condenser is discharged). However, he pointed out, Maxwell only admitted closed currents, and explained open currents in terms of the behaviour of dielectrics. The closed currents are called conduction currents, those caused by a displacement of the inductive fluid are called displacement currents; closed circuits consisting entirely of displacement currents will figure, Poincaré tells us, in Maxwell's theory of light. Conduction currents must obey the laws prescribed by Ohm, Joule, and Ampère if they are to agree with experiments, but nothing is known about displacement currents and Maxwell supposed that they obey Ampère's law and the laws of induction, but neither Ohm's nor Joule's laws. As Poincaré acknowledged, although it is true that this hypothesis was not introduced in the *Treatise* by name, "if the word is not in the work of the physicist, the thing is". In Maxwell's *Treatise*, the inductive fluid is called electricity, and the electricity of dielectrics is supposed to be elastic while the electricity of conductors is inert.

Some pages later, having established what potential energy of an electrical system must be in Maxwell's theory, Poincaré observed that a two-fluid theory version of Maxwell's theory could be made to work, but it was more complicated than a one-fluid theory (an example of Poincaré's ideas about theory choice being based in part on convenience in explanation), and deduced that Maxwell's hypothesis of the inductive fluid is only transitory and will be replaced by something better when the progress of science permits. Several more pages later, he remarked that it would be possible to give the impression, which several people believe, that Maxwell regarded electric displacement as the actual displacement of actual matter. However, "the basis of his thought is quite different as we shall see later on."

Poincaré then turned to the force exerted between electric conductors. Maxwell's idea, he said, as with all his theories, sought to avoid action at a distance, and presented attraction and repulsion as being due to the pressure on ponderable matter transmitted across the dielectric material. Poincaré developed this idea mathematically over a few pages and concluded (p. 73) that it could only be made to work if the laws of an elastic fluid in the dielectrics differ absolutely from the laws of elasticity in every material body we know, from the laws of elasticity for the luminiferous ether, and indeed from the laws we are led to for the elasticity of an inductive fluid. While breaking with inveterate customs could allow one to accept this paradoxical conclusion, it was not compatible with other parts of Maxwell's theory and should be rejected. But then, Poincaré reminded his readers, he had already dismissed the theory of the inductive fluid as provisional.

However, graver difficulties lurked in Maxwell's theory. As Poincaré now remarked (p. 75), it was incompatible with the fundamental hypothesis that energy was localised in a dielectric as a form of potential energy. A kinematic theory of this energy can be made to work, he said, on the further hypothesis that the dielectric is full of turbulent motion, but to do so subjects it to great difficulties.

After a chapter on magnetism, Poincaré turned to the three laws of electromagnetism, which were firmly grounded in experiment, then to electrodynamics, and then to the theory of induction as first presented by Helmholtz and shortly afterwards by Lord Kelvin. Then he presented Maxwell's theory, which he said was different and more complete in some respects. Moreover, if he had presented Maxwell's ideas up to this point as provisional and lacking in objective reality, now (p. 136, Poincaré's emphasis) "*On the contrary, we touch here, I believe, on the true thought of Maxwell*".

Maxwell, said Poincaré, made two hypotheses. First, the coordinates of the imponderable fluid depend on the coordinates of the molecular material of the body that is subjected to electric phenomena and also on the coordinates of the molecular materials of the hypothetical fluid (the positive and negative electricity of the ordinary theory), but this dependence is governed by some law we do not know. Second, the electrodynamic potential of a systems of currents is in the form of kinetic energy. On the second claim, Poincaré was in complete agreement with Maxwell (*Treatise*, Vol. 2, p. 211). But the first point shows that not even Poincaré could accept Maxwell's ideas about electric charge and current.

In Chapter XI of the *Électricité et Optique*, Poincaré briefly noted some of the inconsistencies he had found in Maxwell's theory and then turned to the electromagnetic theory of light. He rightly regarded one of the most important consequences of Maxwell's theory, one that "merits on its own all our admiration" (p. 155), was the proposed identification of the fluid ether due to Fresnel for the propagation of light and the fluid ether invoked by Maxwell for the propagation of electro-magnetic phenomena. Poincaré noted the experimental results tending to confirm this identity, concluding with Hertz's, which he called (p. 164) a very satisfactory verification of the electromagnetic theory of light.

One phenomenon, however, defied a complete explanation although it had been discovered by Faraday back in 1845. This was a connection between light and magnetism, specifically that a magnetic field will rotate the plane of polarisation of plane-polarised light. As Poincaré summarised the matter (p. 197), when Maxwell wrote his *Treatise* it was known that Franz Neumann's theory was contradicted by experiment, but some formulations due to Airy seemed to be in better agreement. Poincaré judged that Maxwell's explanation lacked rigour, but he shared Maxwell's opinion (*Treatise*, Vol. 2, p. 211) that "We must therefore conceive the rotation to be that of very small portions of the medium, each rotating on its own axis. This is the hypothesis of molecular vortices." However, Maxwell had confessed that he found it impossible to assign a form to the law connecting the displacement of the medium with the variation of the vortices, and had put his trust in Helmholtz's great memoir on vortex motion in fluids. Poincaré gave an analysis of the problem along those lines, only to conclude (p. 212) that here "Maxwell seems to have completely abandoned the electro-magnetic theory of light." But he did concede that Helmholtz's formulas seemed to be equally difficult to apply to the problem at hand.

Many pages later, Poincaré turned to the task of finding under what conditions Maxwell's equations and those given by Hertz are the same. He found (p. 376) that three equations must hold, under the condition that all magnetisation is permanent and is not changed by the motion of the magnet. He noted that these conditions would not hold if the magnet is heated, and so the equivalence would lapse.

These remarks by Poincaré indicate how a formidably gifted mathematician can sort out the relationships between conflicting theories. Yet it is Maxwell's name, not Poincaré's, that is more visible today, despite the fact that Maxwell's theory proposed a baffling theory of dielectrics based on a conception of their nature that proved impossible to accept. Almost paradoxically, Maxwell's *Treatise* has emerged as one of the great scientific works of the nineteenth century. The principal reason is, as Einstein observed in his essay of 1931 (the centenary of Maxwell's birth), that Maxwell changed our conception of reality away from points and onto continuous fields, writing "This change in the conception of reality is the most profound and the most fruitful that physics has experienced since Newton." It is Maxwell's name, attached to the eponymous equations, that is best remembered, while the contributions of Poincaré and perhaps even more those of Lorentz, stand only as the most important milestones on the path that leads to Einstein and so to the modern theories.

Notes

1. *Électricité et Optique*, first edition 1890, second edition – the one used in this article – 1901.
2. The full title is *A Treatise on Electricity and Magnetism*, first edition 1873, third edition – the one used in this article – 1891.
3. This follows the thorough account in (Buchwald, 1985, pp. 24 et seq.).
4. This led to his remarkable work on the three-body problem in 1893, see (Barrow-Green, 1997).

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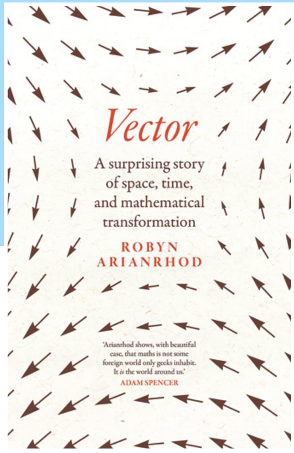
BOOK REVIEW
VECTOR: A SURPRISING STORY OF SPACE, TIME, AND MATHEMATICAL TRANSFORMATION

by *Robyn Arianrhod*
University of Chicago Press, 2024. Hardback & Paperback, 445 + xxvii pp., £23-£28



An interest in the life and science of James Clerk Maxwell's friend Peter Guthrie Tait led me many years ago to write a pair of articles on Tait and his promotion of quaternions. At that time there was just one book devoted to the development of vectorial systems, Michael J. Crowe's *A History of Vector Analysis* (Crowe, 1967) and so that was my main source. Robyn Arianrhod's book, *Vector*, surpasses that of Crowe in its breadth and clarity, relegating historical references and some of the technical details to chapter endnotes, to produce a flowing, largely accessible and engaging argument.

The stars of the book are the vector and the tensor and, from the off, Arianrhod is keen to bind them to the researches of Maxwell and Einstein:

> The first major physicist to recognize the power of vector language was the gently eccentric nineteenth-century Scottish laird, James Clerk Maxwell... His initial theory [electromagnetism] was intuitively 'vectorial', but once he learned that vectors were actually a 'thing', with their own mathematical rules, he realized that they were the right tools for expressing his discovery more succinctly and elegantly. ...
>
> Einstein did for tensors what Maxwell had done for vectors: he was the first major physicist to show their practical power.

(We should note in passing that Maxwell did indeed recognise the vectorial nature of his equations, including in his 1871 paper to the London Mathematical Society: see https://clerkmaxwellfoundation.org/MathematicalClassificationofPhysicalQuantities_Maxwell.pdf.)

After preliminary chapters on the rise of algebra and calculus, the early history of the concept of a vector is covered, including the observation that Newton encapsulated the vector concept in his definition of force and used pure geometry for the composition of forces via the parallelogram rule.

Fast forward to the 1830s when William Rowan Hamilton began his studies. Hamilton was aware of the connection between i ($\sqrt{-1}$) and rotation from his study of works by Jean Bernoulli and Euler, and of how such rotations could be given graphical form in Argand's complex plane. He also knew how to add and multiply complex numbers but, somewhat unsure about how to combine rotations, he dropped i altogether and just studied the algebra of 'couples'. The product of two complex numbers conceptualised as directed line segments, proved to be another complex number associated with rotation in the complex plane. Could the same approach work for rotations in 3-dimensional space? Hamilton explored the possibility of using triples but eventually dropped them in favour of quadruples. In combination with the properties of complex numbers they would form the algebra he needed, so long as he defined the product of rotations in two orthogonal planes as the negative of a rotation in the third plane ('anti-commutativity'). These new entities which he called 'quaternions' consisted of three vector quantities and a scalar. When Paul Dirac and Wolfgang Pauli developed a relativistic quantum mechanical description of electron behaviour in the inter-war years, they found that the spin angular momentum components are related to each other according to the Hamiltonian scheme, allowing for the efficient functioning of MRI machines for non-invasive diagnoses.

In exploring operations on matrices a decade and a half after the invention of quaternions, Arthur Cayley developed another non-commutative algebra. Matrices can also be used to describe rotations in three-dimensional space but the number of calculations required is greater than when combining quaternions. This efficiency, so important when using computers, lends quaternions an advantage, for example in aircraft and rocket guidance systems today.

Hermann Grassmann's vector system, *Ausdehnungslehre* (or 'theory of extensions'), arose from envisaging points extended to make lines and lines stretched to make planes. Grassmann successfully applied it to electromagnetism twenty years before Maxwell's theory. Mathematicians struggled with its complex terminology and concepts but, according to Arianrhod, it would prove 'more useful in the later generalizations that would ultimately lead to modern tensor analysis.'

Hamilton worked on quaternions to the end of his days but well before then they had a new champion in Peter Guthrie Tait, a prodigious talent in mathematics and a lifelong and influential friend of James Clerk Maxwell. When Tait was elected to a Cambridge Fellowship in 1852, he 'treated himself to a copy of Hamilton's *Lectures on Quaternions*, hot off the presses' and read the first six chapters. Two years later, as he was appointed professor of mathematics at Queen's College, Belfast, he studied the remaining chapters. Hamilton was only a hundred miles away in Dublin, so their correspondence was supplemented with face-to-face meetings.

As Tait left for Ireland, Maxwell graduated as Second Wrangler in 1854 without much preparation. He turned immediately to the study of electromagnetism, guided in his reading by William Thomson. He learnt of the differential operator we now call the Laplacian and of the role of changes in electric and magnetic fluxes in electromagnetism. And following Faraday's researches on lines of force, he began to conceptualise a field of force for electricity and for magnetism, and to see the possibilities that partial differential equations might present for describing phenomena. In his landmark paper on the electromagnetic field, published in 1865, he described the key quantities as having magnitude and direction.

Tait, meanwhile, had delved into the researches on heat undertaken by Fourier and Thomson, researches in which there was a role for nabla in describing the changes in temperature through time and space. Hamilton's *Quaternions* gave nabla in a vector form akin to the modern

$$\nabla = \frac{\partial}{\partial x}\boldsymbol{i} + \frac{\partial}{\partial y}\boldsymbol{j} + \frac{\partial}{\partial z}\boldsymbol{k},$$

where $\boldsymbol{i}$, $\boldsymbol{j}$ and $\boldsymbol{k}$ are orthogonal unit vectors. One of its applications is to turn the potential, a scalar function, into a vector (electric field) and it provides compact forms for a force and for Laplace's equation so central to Maxwell's equations. In general, quaternions' concision makes them conceptually easier than the equivalent Cartesian forms. With Hamilton's death in 1865, it was Tait who took up the cudgel, seeking applications of quaternions to physics in his 1867 *Elementary Treatise on Quaternions*. Rather incongruously, Tait's collaboration with William Thomson, *Treatise on Natural Philosophy*, published the same year, featured only Cartesians because Thomson was so opposed to the 'unmixed evil' of quaternions.

In the mid-1860s, Tait advised Maxwell to proceed no further on electromagnetism until he had read the latter sections of his book on quaternions in which the power of the Laplacian was demonstrated. Maxwell recognised quaternions as a 'method of thinking' and wanted them in his *Treatise on Electricity and Magnetism*, but few people were familiar with them. Speaking at the London Mathematical Society in 1871, he divided vectors into forces, related to distances (line integrals), and fluxes, related to area (surface integrals). He was soon defining 'divergence', 'curl' and 'grad' in terms of nabla, though for his groundbreaking *Treatise* he used both the vectorial and Cartesian forms.

'For our story', claims Arianrhod, 'the key Maxwellian is an eccentric telegrapher, Oliver Heaviside, for he is the one who extended Maxwell's whole-vector approach and turned it into modern vector analysis'. Heaviside was indeed first employed as a telegrapher but a paper on the Wheatstone bridge, referenced by Maxwell in his 1873 *Treatise*, marked him out. He turned to writing on electrical and telegraphic theory and on mathematics, but his mockery of quaternions brought him into direct conflict with Tait. Following Maxwell, Heaviside's attention was on vectors and their scalar and vector products but stripped of the notion of imaginary elements. His unit vectors, $\boldsymbol{i}, \boldsymbol{j}$ and $\boldsymbol{k}$, with square 1 rather than and, as here, written in bold type, immediately caught the attention of leading physicists.

As is often quoted, Heaviside reduced Maxwell's equations to four – two divergence equations, (vector forms of the Gauss-Coulomb laws) and two involving the curl of the field (Faraday's and Ampère's laws). But Arianrhod stresses that Maxwell had already reduced them from twenty-four to just five whole-vector equations before Heaviside, effectively one each for the equivalents of $\boldsymbol{\nabla}\cdot\boldsymbol{B}$, $\boldsymbol{\nabla}\times\boldsymbol{E}$, and $\boldsymbol{\nabla}\cdot\boldsymbol{E}$, plus one for the curl of $\boldsymbol{B}$ and another for the mechanical force created by the electric and magnetic fields. In fact, it was Heaviside who wrote Maxwell's equations in terms of $\boldsymbol{E}$ and $\boldsymbol{B}$ and without recourse to potentials, bringing out the symmetry between the electric and magnetic fields in the process, nothing less than a 'masterstroke' according to Arianrhod. *Electromagnetic Theory* was published in three volumes, and it was in the first volume of 1893 that Heaviside laid out the rules of vector analysis. Vectors finally ceased to be just the imaginary part of quaternions; they were real, the rules of their mathematics were shown to successfully describe physical phenomena.

The American mathematician, Josiah Willard Gibbs, was also drawn to vectors through reading Maxwell's *Treatise*. From his vector analysis, developed at the same time but independently of Heaviside's, we have the dot and cross notation for the scalar and vector products. Gibbs also read Grassmann's work and was taken with the German's 'inner product', a scalar product that is valid regardless of the dimension in which the application arises. In his *Elements of Vector Analysis*, he praised Grassmann's system and its unification with quaternions in the hands of William Kingdon Clifford, whilst ignoring the contributions of Hamilton and Tait. And by arguing that quaternions are useless in physics he so angered Tait that the Scotsman dubbed the Gibbs vector a 'hermaphrodite monster' in a piece for *Nature*. Arianrhod leans heavily on Crowe's earlier book in describing the unpleasant 'vector wars' that followed.

Tait had shown that when a frame of reference is altered, say by rotating the axes, all coordinates and vector components change, though not vector magnitudes. Moreover, scalar and vector products in the original frame of reference remain unaffected by the change of frame of reference. Tensors emerged from the mathematicians' attempts to generalise this invariance and the algebraic structure of vectors, paving the way for Einstein's tensor theory of general relativity. With the failure of the Michelson-Morley experiment to detect the aether, Hendrik Lorentz fashioned a set of coordinate transformations between the frame of a stationary observer and that of an observer travelling at a constant speed relative to the stationary one, so that Maxwell's equations are invariant. In 1905, Poincaré made use of these Lorentz transformations to produce a theory of relativity for the case in which the relative motion between observers is constant. Einstein, coincidentally, produced a complete theory of special relativity by a more intuitive route, establishing the length contraction and time dilation provided by the Lorentz transformations from the relativity postulate and the constancy of the speed of light.

Lorentz used whole-vector notation but Einstein would use coordinates and components. It was Einstein's teacher, Hermann Minkowski, who started to develop 4-dimensional vector calculus, adopting a scalar product analogous to that for three dimensions, essentially

$$\boldsymbol{a}\cdot\boldsymbol{b} = a_1b_1 + a_2b_2 + a_3b_3 - a_0b_0,$$

where the final term is that for time. By 1910, his friend, Arnold Sommerfeld was unveiling the 4-D analogues of divergence, curl and grad. He showed that what we now call 'tensors' are needed for the form invariance of the 4-D Maxwell equations.

Earlier, many physicists had considered stress (force per unit area) in various contexts, notably Maxwell in his electromagnetism *Treatise*. He had given the nine components of a quantity he called the 'stress', now dubbed the 'stress tensor', essentially a force acting on a plane. There was no mathematics of tensors as such; here the physics was the horse and mathematics the cart. Sommerfeld recognised that tensors could have wide application in physics but he would need to describe a plane in the same way that a vector describes a line. Yet, a plane has an orientation in space and this required a focus on the plane's normal, specified using a unit vector perpendicular to the plane.

The first mathematical analysis of tensors came from Grigorio Ricci in 1884. Calling tensors 'systems of functions' and tensor analysis 'absolute differential calculus', Ricci's initial focus was on how components of two tensors combine to give the components of a non-commutative tensor product. Vectors have a single index (subscript), matrices have two. In 3-dimensional space, Maxwell's stress tensors have $3^2 = 9$, while in 4-dimensional space-time, the curvature described by the Riemann tensor requires $4^4 = 256$ indexes, and so these figures spiral upwards as the number of dimensions increases. The analysis throws up systems of linear algebra and sets of combination rules leading to the conditions for invariance under certain transformations and the identification of covariant tensors. The power of the mathematics arises from what Arianrhod describes as the 'remarkable way the mixed form of the scalar product shows invariance *through its very symbolism*' (her emphasis). This is complex mathematics applied in complex physics but contractions in the mathematics make the physics more accessible. The immediate response to Ricci's mathematical gymnastics however was that surely no application would be found, but this was to change in 1900 when Ricci was joined by Tullio Levi-Civita in writing a paper that provided an overview of tensors for the scientific community.

Einstein came to realise that the design of a relativistic theory of gravity was feasible since gravity could be 'made' or 'unmade' by changing the frame of reference. And if light travels along a curved path it takes longer to reach a distant observer and appears to slow down. There is also a gravitational redshift akin to the Doppler effect. But could all these phenomena be rendered mathematical? Einstein needed a metric for the space-time that would do for general relativity what the Minkowski metric does for special relativity. A valiant effort to find such a metric was made by Max Abraham in 1912 but Einstein thought Abraham's reasoning was flawed. In the autumn, Einstein was yet to see how the principle of equivalence could be reconciled with the principle of relativity. (According to the former, observers cannot judge whether they are in a smoothly accelerating lift or in a closed room in a gravitational field. According to the latter, the laws of physics should be the same for all observers.) He came to see the Minkowski metric as a special case of the metric he was seeking but only after his friend, Marcel Grossmann, had directed him to the Riemannian manifold and its associated metric and to the overview paper on the mathematics of tensors. Grossmann identified one of Ricci's tensors as having the correct mathematical form for a gravitational potential. Meanwhile, Minkowski and Sommerfeld had recast Maxwell's electric and magnetic fields into a single tensor in 4-D space-time which was independent of the frame of reference.

Some of the building blocks were now in place for a general theory of relativity and Einstein and Grossmann worked day and night on outline papers (the *Entwurf* papers of 1913-14), Einstein on the physics and Grossmann on the associated mathematical structures. Yet, the gravitational equations were not fully covariant and so Levi-Civita was brought in to help Einstein find the right gravitational field tensor. This led to the fully covariant general theory of relativity in November 1915. There are ten equations of general relativity packed into just one. They account for the precession of the perihelion of Mercury, and the eclipses of 1919 and 1922 confirmed the bending of light as the theory predicted. In his summary paper of 1916, Einstein was full of praise for the mathematicians with whom he had worked. Without the development of vectors and tensors his researches would have been even more troublesome.

Some issues relating to conservation laws and to divergence that were not addressed by Einstein were successfully tackled by Emmy Noether in 1918. She showed that a single fundamental principle embodies physical conservation laws and mathematical symmetries, applicable in general relativity though not exclusively. As a researcher in general relativity herself, Robyn Arianrhod is certainly well-placed to appreciate Noether's contribution.

Vectors, tensors and matrices have continued to contribute to scientific discovery ever since. Paul Dirac used them in his 1927 development of quantum electrodynamics (QED), uniting Maxwell's electromagnetism, special relativity and the quantum mechanics of the electron. The quantum field theory that emerged from it allowed Dirac to predict the existence of positrons. And with QED's power to analyse particles in particle colliders, the boson predicted by Peter Higgs in 1964 was detected by CERN's Large Hadron Collider in 2012.

If there is one lesson to be learnt from Robyn Arianrhod's fine book it is that vectorial methods were not cultivated in a vacuum (notwithstanding their usefulness in describing electromagnetic phenomena in such); their very existence is inextricably linked to developments in electro-magnetism and relativity. There are novelties in the algebras that emerged, and difficulties in interpreting rotations in space and finding the best metrics, and yet out of the mix comes a new understanding of how the universe works. In *Vectors*, the interplay between mathematics and physics is both revealing and riveting. This book is a veritable *tour de force*.

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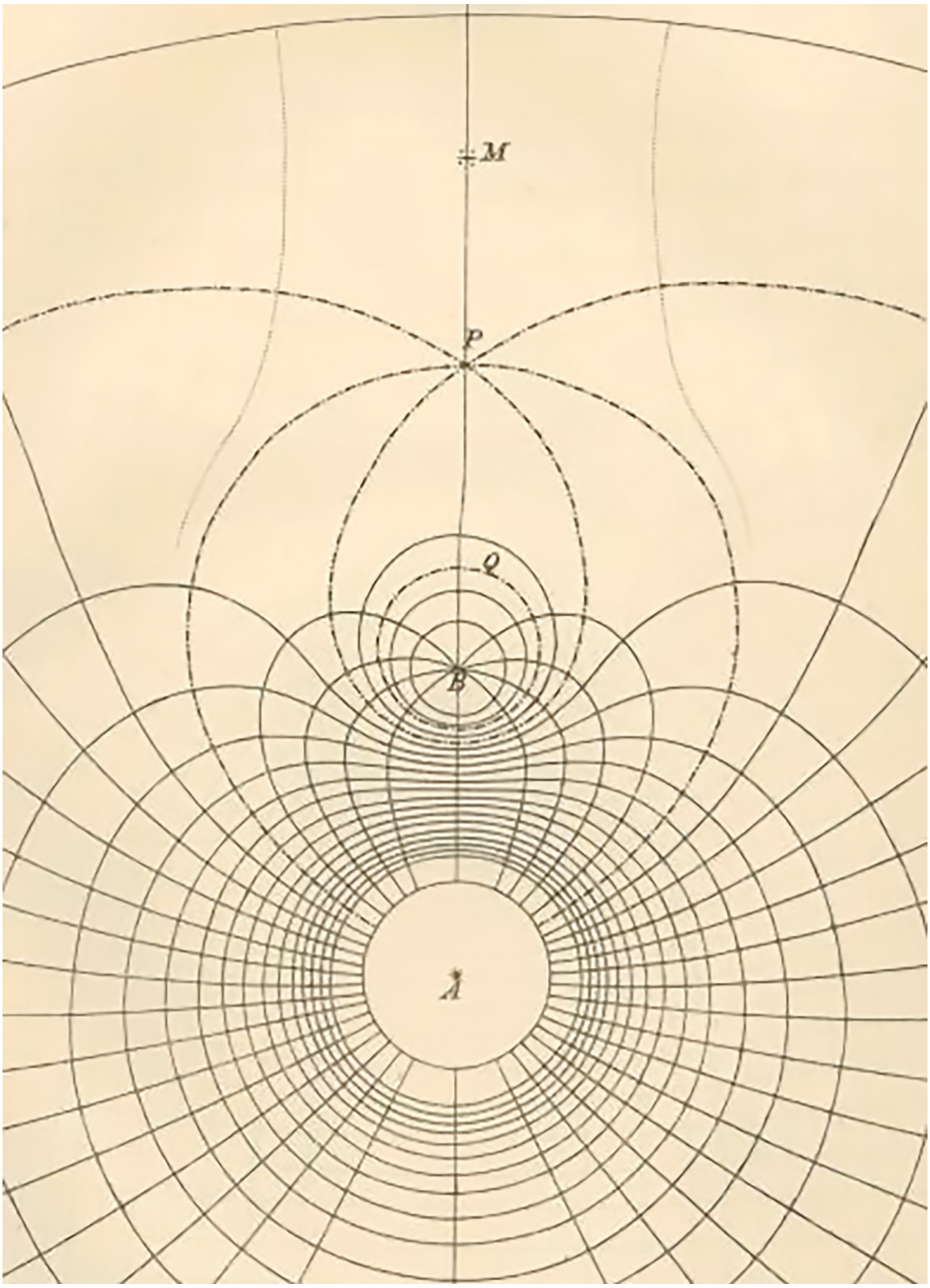

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