



newsletter

OF THE JAMES CLERK MAXWELL FOUNDATION

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From Maxwell to Higgs

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Higgs found

At about 3.00pm on the afternoon of Tuesday 8 October 2013, a car pulled to a halt in Heriot Row in Edinburgh. An ex-neighbour got out and raced across to street to intercept Professor Emeritus Peter Ware Higgs walking home. She stopped him and said "Congratulations! My daughter just called me from London and told me about your award!" to which Peter Higgs replied "What award?" This was the moment when Peter Higgs first heard that the Nobel Foundation had awarded the 2013 Nobel Prize in Physics jointly between himself and the Belgian physicist Francois Englert.

Maxwell's territory

James Clerk Maxwell was born on 13 June 1831 at 14 India Street in Edinburgh's New Town, by coincidence a short distance from Peter Higgs' home since 1967. In 1841, James's father decided to send James to the Edinburgh Academy to complete his schooling. During that time James stayed with his aunt Isabella Wedderburn at 31 Heriot Row, the very same street where our tale began.

Peter Guthrie Tait

The secretary to the Duke of Buccleuch sent his son, Peter Guthrie Tait, to Edinburgh Academy and, although they were of the same age, Maxwell ended up in a class a year ahead. They struck up a friendship that was to last for the rest of Maxwell's life.

Professor James Forbes

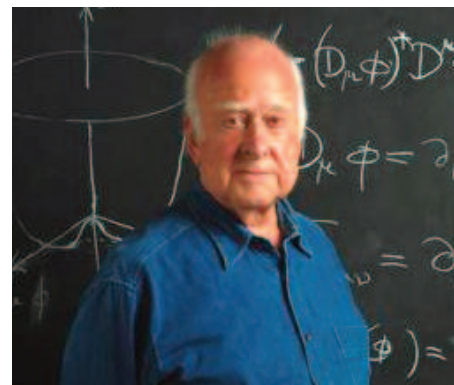
John Clerk Maxwell, Maxwell's father, an advocate and Fellow of the Royal Society of Edinburgh, probably took young James along to meetings there. At the age of 14, Maxwell authored a paper 'On Oval Curves' which in 1845 was read to the Royal Society of Edinburgh on his behalf by Professor James Forbes. Maxwell attended the University of Edinburgh where one of his mentors was the same James Forbes. After three years at Edinburgh, Maxwell decided to complete his degree at Cambridge.

Cambridge

Peter Guthrie Tait was already at Peterhouse College, Cambridge when Clerk Maxwell came to Cambridge. In 1852, Tait became Senior Wrangler at Cambridge whilst, in 1854, Maxwell became Second Wrangler. They both won the Smith's Prize. Maxwell became a Fellow of Trinity College in 1855.

Aberdeen

In 1856, Maxwell was appointed Professor of Natural Philosophy at Marischal College, Aberdeen. Despite having married the Principal's daughter, Katherine Dewar, he was made redundant when, in 1860, Marischal College merged with King's College to form the University of Aberdeen. However, James Forbes had recently accepted the post of Principal of St. Andrews College (later the University) and his chair at Edinburgh became vacant. Maxwell was unsuccessful and Tait was appointed because he was seen



Professor Emeritus Peter Ware Higgs

as the better teacher. Maxwell offered to come to Edinburgh unpaid but the University turned this offer down!

Kings College London

In 1860, Maxwell was however appointed to a chair at Kings College, London. During his time there he published research on the theory of colour, the dynamics of the electromagnetic field and the kinetic theory of gases.

Maxwell's Electromagnetism

In 1865, Maxwell resigned from Kings College, London and returned to Glenlair, where he wrote most of his 'Treatise on Electricity and Magnetism'. In March 1871, Maxwell was appointed to a Chair of Experimental Physics and to the Directorship of the Cavendish Laboratory at Cambridge. Sadly, Maxwell died of cancer on 5 November 1879.



The Tait Chair of Natural Philosophy

Tait made a great success of his time at Edinburgh and died at the age of 70 in 1901. During his time there, he worked on quaternions, knot theory and the physics of golf. At his death, he bequeathed funds to set up a lectureship in natural philosophy and, in 1925, this was converted into the *Tait Chair of Natural Philosophy*. The first incumbent was Charles Galton Darwin, the grandson of the Charles Darwin. When he took up the post of Master of Christ's College in Cambridge in 1936, he nominated his successor to be Professor Max Born, one of the founding fathers of quantum theory. Max Born had found his way to Cambridge after being driven out of Germany by National Socialism. Professor Nicholas Kemmer succeeded Max Born in 1952. In 1954, Max Born rather belatedly received a Nobel Prize in Physics for his earlier contribution to the development of quantum theory.

The Tait Institute of Mathematical Physics

In 1954, Nick Kemmer was instrumental in the establishment of the Tait Institute of Mathematical Physics across the road from the Department of Natural Philosophy. In 1966, Kemmer's post was renamed the *Tait Chair of Mathematical Physics*.

Peter Ware Higgs

Peter Ware Higgs was born in the Elswick district of Newcastle on 29 May 1929. His father Thomas Higgs graduated from Bristol and joined the BBC as a radio engineer. He was moved to Newcastle where Peter was born. Peter's mother, Gertrude Maud Coghill, came from an Edinburgh family many of whom were eminent physicians. The paternal Higgs' ancestors came from Bristol and from surrounding Gloucestershire.

Peter's family moved from Newcastle to Birmingham when he was about a year old. Early in WWII, he moved to Bristol with his mother. In Bristol, he attended Cotham School and was fascinated by the name, Paul Dirac, that appeared frequently on the honours boards. Paul Dirac had shared the 1933 Nobel Prize in Physics for quantum theory with Erwin Schrödinger and Werner Heisenberg. Paul Dirac's relativistic equation, describing the electron, was recognized as predicting antimatter in the form of the anti-electron or positron. Despite excelling more at

chemistry and mathematics than physics, Peter took up theoretical physics on his arrival at Kings College, London where got a First Class degree in 1950. He then completed an MSc and a PhD in what he himself describes as theoretical quantum chemistry.

In 1949, Peter and a fellow undergraduate hitchhiked to the Scottish Highlands and they found themselves in Edinburgh. Peter immediately fell in love with the city. He was awarded an 1851 Exhibition Senior Postdoctoral Studentship and in 1954 – 56 spent part of his time at the University of Edinburgh. He subsequently spent time as an ICI Fellow at Imperial College in London and was disappointed at not being able to work with Abdus Salam. In 1960, after a temporary lectureship at University College, London, he was appointed as a lecturer at the Tait Institute in Edinburgh headed by Nicholas Kemmer, Abdus Salam's former supervisor.

Spontaneous symmetry breaking

Peter continued his interest in the symmetries underlying many physical phenomena. He took an interest in condensed matter theory and, in particular, in what is known as spontaneous symmetry breaking in systems such as ferromagnets and superconductors. In a ferromagnet, the iron atoms behave like dipole magnets with north and south poles at opposite ends, rather like compass needles. In a system above the Curie temperature, these magnetic dipoles are randomly oriented and the overall magnetization disappears. Thus, above the Curie temperature, rotating such a ferromagnet makes no difference as it has a rotational symmetry. However, below the Curie temperature, these elementary magnetic dipoles may align themselves in a particular direction because this has the advantage of having lower energy. The system itself still has the original symmetry but the symmetry of the lowest energy state does not exhibit the same symmetry. It now has a 'spontaneously' chosen preferred direction breaking that symmetry.

The Goldstone Theorem

Yoichiro Nambu was looking to see if the same could be true in a relativistic elementary particle system. He played around with theoretical models that kept the underlying symmetry but looked for the lowest energy states that 'spontaneously' broke this symmetry. These attempts were not entirely

successful and in particular Jeffrey Goldstone, then of Trinity College, Cambridge showed that in such models there would exist zero mass scalar particles. This work was published jointly with Abdus Salam and Steven Weinberg who re-appear in this story later. This became known as the *Goldstone Theorem* and was a serious problem for the *Nambu* programme as such massless spin-less particles would be easily found and would be more readily emitted by stars than photons.

A symmetric bowl

Imagine you have a bowl that has a shape that is rounded and not flat at the bottom and is symmetric about an axis through its centre. You can rotate such a bowl around that axis and it always looks the same. If you were to put in a small ball bearing, it would sit at bottom. This is the lowest energy state of that ball and rotating the system about the symmetry axis does not change anything. It still has the symmetry it started with. If we push the ball away from the bottom of the bowl, we have to do work to push it up the sides. We have two distinct ways of doing this. Either E-W or N-S. Any other direction is just a combination of these two. Since we do work in both cases this corresponds, in what we talk about later, to two massive scalar particle modes.

The wine-bottle or Mexican hat potential

The particular shape of the bowl we have just been discussing will depend on two parameters, which, in the above case, we can take to be both positive numbers. If, however, we make one of these parameters negative, the bowl now takes on the shape similar to that of a sombrero or, if you prefer, the bottom of a champagne bottle. If we rotate about the symmetry axis, the system is still symmetric. However, if we were to put into this our small ball bearing, then its lowest energy state is no longer in the centre but away from the centre at the bottom of the depression or trough in the bottle or hat. This ball bearing will have chosen to sit at some angle in the trough and, when we turn the bottle or hat about its symmetry axis, the lowest energy state chosen by the ball bearing will move with the bottle or hat – it will no longer have the symmetry of the empty bottle or hat. The lowest energy state has 'spontaneously' broken the symmetry. It also is true that if you push the ball up the sides of the trough you will need to do some work so this will correspond, in what we discuss later, to a massive particle.

If we push the ball along the bottom of the trough, we need do no work and, in fact, once moving the ball will continue to move. (There is of course no friction in our ideal bottle or hat!) This is just the Goldstone Theorem, and this seemed at that time to be inevitable in such theories.

The golden year of 1964

Several papers had appeared which stated that the Goldstone Theorem could not be overcome. In particular, a 1964 paper by Walter Gilbert made statements that provoked Peter into thinking about the problem and, after a weekend spent in Edinburgh, he realised, with inspiration from the world of condensed matter, that there was a way out. The previous proofs had not considered ‘gauge theories’, such as quantum electrodynamics (QED), the quantum relativistic version of Maxwell’s classical theory of electromagnetism. In his first paper accepted by *Physics Letters*, Peter showed that there could be such a way out.

Maxwell’s classical equations in a vacuum give rise to electromagnetic waves where the electric and magnetic fields are directed transverse to the direction of propagation and perpendicular to each other. In other words, classically the wave can be polarized and there are just two independent ways in which the electric field can point e.g. either horizontally or vertically. The waves travel at the speed of light, c , and in the quantum version the energy of the wave is carried in quanta known as photons travelling with the same speed, c . Photons are therefore required by relativity to have zero mass. The photon is a massless ‘vector’ particle of spin 1 and has just two independent spin states as a result, corresponding to the classical polarization directions. We would describe it as having two degrees of freedom. A massive particle does not travel at the speed of light and therefore can have a third spin direction and hence three degrees of freedom.

Peter Higgs published his second 1964 paper in *Physical Review Letters* and took Goldstone’s model with two scalar fields and coupled them to a Maxwell-like field. In the ‘wine-bottle’ potential, the massless Goldstone mode (the mode corresponding to motion around the trough) is absorbed by the Maxwell field. The resultant field is that of a spin-1 particle with three spin components, in other words that of a massive vector particle. The remaining scalar field, corresponding to sideways motion in the trough, is a leftover massive spin-0 or scalar particle, later to become known as a *Higgs boson*. Each scalar boson has just

one way of moving and therefore has just one degree of freedom.

This theoretical mechanism for giving mass to the vector particles of the gauge field was shown by two other groups – Robert Brout and Francois Englert earlier in Brussels and Gerry Guralnik, Carl Hagen and Tom Kibble later at Imperial College, London. This mechanism has recently become known as the Brout-Englert-Higgs (BEH) mechanism. Peter Higgs was the most explicit in his mention of the leftover massive scalar boson, encouraged in part by the rejection of the first draft by a referee of *Physics Letters* based at CERN!

Peter followed this up with a more detailed third paper published in 1966 but written in 1965 whilst on sabbatical leave at the University of North Carolina. Tom Kibble published another paper in 1967 where he showed how to apply this for higher symmetries, allowing some vector particles to acquire mass whilst leaving others massless. However, all of the six authors were looking to apply this to the strong nuclear forces following Nambu. As a result it was left to others to find the correct application – namely unifying the weak nuclear interaction with the electromagnetic interaction.

The electroweak synthesis

The relativistic quantum field-theoretic version of Maxwell’s electromagnetism, quantum electrodynamics (QED), is arguably the most successful theory in terms of its theoretical predictions and experimental verifications. Combining quantum theory with Einstein’s special relativity, Paul Dirac was able to establish the relativistic quantum mechanical description of the electron and predicted the existence of its anti-particle, the positron. Processes, such as the scattering of electrons, are described by the exchange of photons. In other words, the massless photon is the particle carrying the electromagnetic force between charged particles.

Feynman, Schwinger and Tomonaga shared the Nobel Prize in Physics in 1965 for showing that QED was ‘renormalisable’ – calculations to all orders give physically acceptable results. For example, theoretical calculations of a subtle effect, the Lamb shift in the spectrum of hydrogen, agree with the experimental measurements to at least one part in a million.

The weak nuclear force was known from the early days of looking at the beta decay of nuclei. This force has similarities to the electromagnetic force but is of much shorter range. That meant that, if it too had a spin-1 force carrying gauge boson, its mass had to be similar to that of a silver atom! As early as 1960, Sheldon Glashow had written down an electroweak model in which he combined the electromagnetic and weak forces. However, he put the masses of the weak force gauge bosons into his equations by hand which meant that no meaningful calculations would be possible.

In 1967, Steven Weinberg used the BEH mechanism as used by the Nobel Foundation, together with a version of the Glashow electroweak model combined with the modifications of Tom Kibble’s 1967 paper. He selectively gave mass to the three W^+ , W^- and Z^0 spin-1 weak gauge bosons whilst keeping the photon massless. This required the introduction of two charged and two neutral Higgs fields, three of these being absorbed to give mass to the spin-1 weak gauge bosons. The one leftover Higgs field gave rise to the massive Higgs boson of the Standard Model. For this work Sheldon Glashow, Abdus Salam and Steven Weinberg shared the 1979 Nobel Prize in Physics.

Quantum Chromodynamics (QCD) and the Standard Model

We now know that the constituents of the nucleus, the protons and neutrons are themselves made from three quarks. The strong forces between these quarks are carried by eight massless spin-1 particles, the gluons. The symmetry of the strong interactions is also a gauge symmetry but more complicated than that of quantum electrodynamics. Nevertheless, Gerardus ‘t Hooft and Martinus Veltman showed that such theories are also renormalisable. For this, they shared the 1999 Nobel Prize in Physics. Putting together the theories of QED and QCD gives us the Standard Model (see Figure 1) of particles and interactions. All of the particles that take part in strong interactions are made up of six varieties, or ‘flavours’, of spin-1/2 quarks, each of which comes in three ‘colours’. There are also six other spin-1/2 particles being three electrically charged leptons (the electron and two heavier particles) and three massless neutrinos.

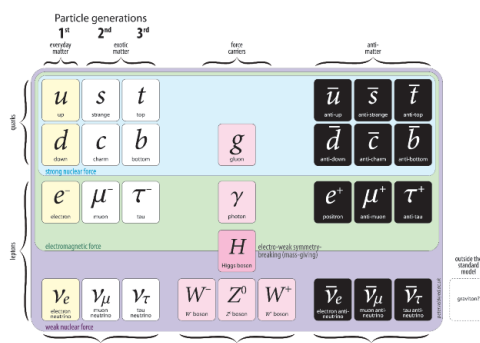


Figure 1: The Standard Model



These spin-1/2 particles, or ‘fermions’, are what we call the particles of matter. In the Standard Model, Weinberg introduced additional ‘Yukawa-like’ interactions between the Higgs field, the quarks and charged leptons. This way of giving mass to the fermions was known earlier than 1964 and is not part of the BEH-mechanism that gives mass to the spin-1 force carriers. It is also important to point out that the masses of the quarks that make up the strongly interacting particles (or hadrons, for example protons and neutrons) account for only about 1% of their mass. The rest of the measured mass of such composite particles comes from the energy associated with the motion of the quarks and gluons inside. The Higgs does not give *all* of the mass of *all* observed particles but does give the mass of the fundamental particles in the Standard Model.

The missing piece of the Standard Model puzzle

In 1983, the weak gauge boson partners of the photon were found at CERN and the Large Electron Positron Collider (LEP) subsequently measured their precise properties. The discovery of the fundamental particles of matter, the leptons and quarks, therefore took about a century culminating with the discovery of the top quark at Fermilab in the US in 2009. The missing piece of the Standard Model jigsaw puzzle was therefore the Higgs boson itself. Its mass is not predicted by the BEH mechanism as it is determined by a different and otherwise unknown parameter. On July 4 2012, at a seminar in Geneva, it was announced that the two experiments, ATLAS and CMS, at CERN’s Large Hadron Collider had discovered a particle of mass $126 \text{ GeV}/c^2$, consistent with the Standard Model Higgs boson. Each experiment reported their results independently and each received standing ovations as well as sheer whoops of delight. This was an extraordinary historical moment. Peter Higgs even shed a tear on hearing the news! That day, however, was in Peter’s words “*the day to celebrate the heroic achievements of the experimentalists*”.

By March 2013, further analysis and data had improved these results and showed that the particle discovered is most likely to have spin-0. The measured rates for the modes in which the Higgs boson decays are consistent with the masses of the products of those decays, suggesting they indeed get their masses from the Higgs field. The LHC will be shut down in 2014-5 for maintenance and major upgrades. When it restarts it will be operating at or near its design energy and at very much higher intensities. This will enable more precise tests of the properties of the Higgs boson and the Standard Model. Indeed we already know that the Standard Model is not complete as the neutrinos are not massless but have small non-zero masses. There are also too many unknown parameters in the model that are not predicted a priori and have to be determined experimentally.

There are extensions to the Standard Model, such as supersymmetry, that predict a whole new set of particles at higher masses but, as yet, there are no hints of these. Supersymmetry has many attractive features and may even give us a clue to the origin of the elusive ‘Dark Matter’ in the Universe. The Higgs boson discovery is the closing of a chapter rather than of the book. We look forward to what the next chapter in this story may bring and have no idea how long this book is likely to be.

Äntligen här! Here, at last!

On October 8 2013, the Nobel Committee awarded the 2013 Nobel prize in Physics to Francois Englert of the University of Brussels and Peter Higgs of the University of Edinburgh for “*the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles and which recently was confirmed through the discovery of the predicted fundamental particle by the ATLAS and CMS experiments at CERN’s Large Hadron Collider*.” The custom and practice of the committee is to award to three individuals at most and not to a group. It did not award the possible third share to CERN, although it is

strongly mentioned in the citation. It also could not award the third place to Robert Brout as he sadly died in 2011. By leaving this third place vacant perhaps the Nobel Committee intended to acknowledge this fact silently.

So 49 years after he wrote his first two papers, Peter Higgs travelled to Stockholm for Nobel Week. For Peter, this began on 4 December with lunch at the Swedish Ambassador’s residence in London for current and past British Laureates and ended with the final banquet at the Swedish Royal Palace on 11 December. On 8 December, the two 2013 Laureates in Physics received a standing ovation for their Nobel Lectures from an overflowing Aula Magna auditorium at the University of Stockholm.

The Nobel Prize is seen as the ultimate accolade of course but Peter has received many awards and is to receive the Freedom of the City of Edinburgh in due course. This does not come with any special privileges but is a suitable recognition that Peter has adopted Edinburgh as his home for more than half a century. He now walks the same streets that Maxwell and Tait must have walked before him. We have seen how their paths have crossed over the years in terms of both geography and in their careers in physics. Maxwell’s work took the electric and magnetic forces and unified them into the one electromagnetic force. Peter Higgs’ contribution was crucial in helping others in unifying the electromagnetic and weak forces. The further unification with the strong force and thereafter with the gravitational force is a longer-term goal.

We should not forget that Maxwell remains not only the inspiration for such giant strides in theoretical physics but also that his work provides the fundamental basis for almost all of the advanced modern technology without which this discovery could not have been made. ■



Portrait of Sydney Ross by Robert Hildreth

PROFESSOR SYDNEY ROSS, BSc, PHD, HON.DSc, CORRFRSE (6/7/1915 – 4/12/2013)

Sydney Ross was the Hon. President of the James Clerk Maxwell Foundation, a Scottish Charity, which he set up in 1977. Sydney laboured tirelessly to achieve national and international recognition for Clerk Maxwell, recognition that Clerk Maxwell so richly deserved but had, Sydney felt, not been adequately accorded to Clerk Maxwell, particularly in his native land.

Sydney can take substantial credit that the name of James Clerk Maxwell now ranks with those of Newton and Einstein as one of the greatest of scientists. Sydney also witnessed the statue of Clerk Maxwell in Edinburgh (commissioned by the Royal Society of Edinburgh) and oversaw (and generously contributed to) the purchase, by the Clerk Maxwell Foundation, of the house in Edinburgh where Maxwell was born. Sydney also contributed his books about Maxwell and Maxwell’s scientific colleague (Professor P.G. Tait) to the library of the Foundation.

Sydney was, until he retired, the Professor of Colloid Chemistry at the Rensselaer Polytechnic Institute in the U.S.A. He came over from the U.S.A. when he was Chairman of the Foundation but, when he was no longer able to travel, he kept a close eye on the activities of the Foundation and was sent copies of the minutes of all our meetings.

Sydney passed away peacefully in December 2013. Thanks to his founding of, and interest in the activities of the Foundation, it is now thriving. For example, this year, the Foundation is hosting, along with the British Society for the History of Mathematics, the 400th anniversary of John Napier’s (another celebrated Scottish scientist) invention of logarithms in 1614. The current activity of the Foundation is a fitting tribute to Sydney’s memory.

James Clerk Maxwell Foundation, 14 India Street, Edinburgh, EH3 6EZ
The birthplace in 1831 of James Clerk Maxwell.

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