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Electroweak Thoughts

By **Professor Sheldon Glashow, Metcalf Professor of Physics, Boston University. Nobel Prize for Physics, 1979**

Introduction

Just as James Clerk Maxwell unified electricity and magnetism, his ambitious successors sought to unify some or all of the remaining forces of nature: gravitation, electromagnetism and the two sub-atomic forces, weak and strong. Kaluza, Eddington and Schroedinger each tried to unify gravitation and electromagnetism, a task which also occupied Einstein for decades. None of them had the least success. Yukawa conjectured his *"mesotrons"* as mediators of both weak and strong nuclear forces. They were found amongst cosmic rays in 1948 and now are called pi mesons or pions. They do not mediate weak interactions but physicists once regarded pion exchange between nucleons as the *sine qua non* of the nuclear force. Yukawa earned his Nobel Prize but failed at unification. He was in good company: Heisenberg and Pauli clung to their own dream of a unified quantum field theory until the mid 1950s. Here I will summarize my own experiences on the road toward the unification of weak and electromagnetic forces.

Common origin of weak and electromagnetic interactions?

As a Harvard graduate student in 1956, I asked Julian Schwinger if I could study under his supervision. About a dozen of us had the same idea at the same time. Schwinger gathered us all together in his office and proceeded to assign thesis problems. Charles Sommerfield was told to compute the two-loop radiative correction to the electron magnetic moment. This he did, thereby earning a tenured position at Yale. Daniel Kleitman, told to find the implications of Schwinger's *"global symmetry"* scheme for elementary particles, got his physics degree even though Schwinger's scheme did not long survive. Danny left physics to become a renowned MIT professor of discrete mathematics and later on, my brother-in-law.

Finally Schwinger turned to me, the last aspirant in line. With no further sensible (i.e. doable) problems in mind, he confided to me his belief that weak and electromagnetic interactions, being both vectorial and universal, should have a common origin. He suggested I study non-Abelian gauge theories, like the Yang-Mills model. Charged spin-1 bosons, now called $W^{\pm}$, could mediate weak interactions with the neutral boson identified with the photon. He did not know how heavy $W^{\pm}$s could violate parity and strangeness while massless photons do not. Nor did such a theory seem renormalizable. I struggled for months but found no answers. My thesis concluded contingently that:

> *"a fully acceptable theory of these [weak and electromagnetic] interactions may only be achieved if they are treated together."*

Larger gauge group

In 1958, Kleitman and I set off to Niels Bohr's Institut for Teoretisk Fysik in Copenhagen as newly-minted National Science Foundation Postdoctoral Fellows.

Towards the end of my two-year European junket, I realized that electroweak unification required a larger gauge group than $SU(2)$. The simplest extension sufficed: an additional $U(1)$ factor. I submitted my $SU(2)\mathrm{x}U(1)$ electroweak model to Nuclear Physics in 1960. My photon was a linear combination of the two neutral gauge fields with a mixing parameter now curiously called the Weinberg angle. A heavy neutral boson, Z^0, mediated novel neutral-current phenomena. I once thought that the model was renormalizable with W and Z masses inserted "by hand," but Salam proved me wrong. My model could not encompass nuclear particles without incurring unacceptable strangeness-changing neutral currents. Meanwhile, Salam and Ward proposed several electroweak models based on $SU(2)$ or various larger groups. They published a model identical to mine in 1964 without citing my earlier work.

Spontaneous symmetry breaking

Spontaneous symmetry breaking was considered in condensed matter physics by Anderson and Nambu in 1960 and extended to relativistic field theories by Goldstone in 1962, who illustrated it with the simple example of a complex spinless field. If its $U(1)$ symmetry spontaneously breaks, one of the two scalar fields becomes massless. For systems with larger spontaneously broken symmetries, Goldstone, Salam and Weinberg showed one massless Nambu-Goldstone boson to arise for each broken symmetry generator. None of this seemed relevant to the real world wherein massless spinless particles do not exist.

Remarkable developments

I must digress with a list of remarkable developments in physics that all took place during 1964:

i. The Higgs mechanism was invented,
ii Quarks were proposed as hadron constituents,
iii. The Ω^- baryon was discovered,
iv. The charmed quark was proposed,
v. The notion of quark color arose,
vi. The violation of CP symmetry was discovered,
vii. The Cosmic Microwave Background was detected.

Each of these events plays an important role in electroweak history.

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i. Higgs mechanism and boson

A giant step was taken unknowingly by six authors in three Physical Review Letters written between June and October. They examined spontaneous symmetry breaking in the context of non-Abelian gauge theory. They found each spontaneously broken gauge symmetry to lead not to a massless Goldstone boson, but to the acquisition of mass by the corresponding gauge boson. Two of the papers mention the possible relevance to the now-discarded Sakurai gauge theory of the strong force; none mention any relevance to the electroweak model. The work could have been attributed to Brout, Guralnik, Englert, Hagen, Higgs & Kibble. Instead it is known as the Higgs mechanism with the surviving massive spinless bosons universally called Higgs bosons.

Three years later, Steven Weinberg used the Higgs mechanism to promote my electroweak model to a genuine theory. His *"Theory of Leptons"* introduces a complex doublet of scalar fields with a potential ensuring spontaneous symmetry breaking. An identical model was published a year later by Salam, who expressed confidence in its renormalizability, the proof of which would be provided by 'tHooft and Veltman in 1973. The theory involves only a small number of tunable parameters: the Higgs boson mass and vacuum expectation value, the electron charge and the charged lepton masses. Although the theory offers a correct description of weak and electromagnetic leptonic interactions, it initially attracted little attention because it did not describe nucleons and other strongly interacting particles.

ii. Quarks

Fractionally charged quarks were devised independently by Gell-Mann, Petermann and Zweig. They provide a natural explanation for the many successes of Gell-Mann and Ne'eman's flavor-$SU(3)$ symmetry scheme, sometimes called the eightfold way because it explained why spin-1/2 baryons and pseudoscalar mesons appear as octets of particles with the same spin and parity. Convincing evidence for the validity of the quark model emerged from studies of deep-inelastic electron-nucleon and neutrino-nucleon scattering.

iii. The Ω^- baryon

The lowest mass pion-nucleon resonances comprise an isotopic spin quartet of spin-3/2 particles. In 1962, Gell-Mann placed them, along with their five known strange cousins, into a ten dimensional representation or decimet of the eightfold way. He named the unobserved member of the decimet, Omega-minus, and predicted its mass and decay properties. Just such a particle was discovered by the Samios group in 1964, thereby supporting both unitary symmetry and the quark model: the Ω^- is comprised of three strange quarks.

iv. The charmed quark

In 1964, James Bjorken and I, while on sabbatical in Copenhagen, proposed there to be a fourth *"charmed"* quark, one much heavier than the original three. The four quarks form two doublets, just like the four then-known leptons. Cabibbo mixing could be introduced among the quarks, but the corresponding neutral currents conserve strangeness. We failed to recognize the role charm could play in an electroweak theory. Six years passed before Iliopoulos, Maiani and I showed charm to deserve its meaning as a device to avert evil. The GIM[1] mechanism naturally removes the strangeness-changing neutral currents that bedeviled earlier attempts at electroweak synthesis. With charm, the electroweak model immediately became a genuine theory of the electromagnetic and weak interactions of all known elementary particles. Subsequent experiments offered many confirmations of the theory, not least the discoveries of charmed particles and the weak intermediaries *(Figure 1).*

v. Quark color

How could electroweak symmetry possibly cohabit with the strong interactions? Surely weak and strong symmetries would conflict with one another. Oscar Greenberg planted the seed to the solution with his explanation for the seemingly bosonic behavior of the three quarks in a baryon. He proposed quarks to be *"parafermions of order three,"* an idea which was later reified by the introduction of a new quantum number called quark color. Each flavor of quark: up, down, strange and charmed, comes in three colors, say red, blue and green. These usages, of course, are borrowed and have nothing to do with our senses of taste or vision. In 1973, Fritzsch and Gell-Mann put forward a theory they called Quantum Chromodynamics or QCD: an unbroken $SU(3)$ gauge theory consisting of an octet of gauge bosons acting on color triplets of quarks. Color is the arena reserved for strong interactions, just as flavor is reserved for the electroweak. Soon afterward, Gross, Politzer and Wilczek showed QCD to be asymptotically free, becoming weaker at high energy, but stronger and confining at low energy. Most physicists are convinced that QCD underlies the strong force among hadrons. Our standard theory of elementary particles consists of QCD and the electroweak theory, with the gauge group $SU(3)\mathrm{x}SU(2)\mathrm{x}U(1)$ originally acting on two families of quarks and leptons.

vi. CP symmetry

In the 1950s, physicists learned that two cherished discrete symmetries are not symmetries at all. Charge conjugation, C, and space reflection or parity, P, known to be symmetries of the strong and electromagnetic forces, were both found to be maximally violated by weak interactions. However, the product of these two operations, CP, was built into the structure of the weak interactions and believed to survive as an exact symmetry. Nevertheless, an experiment performed by Fitch and Cronin, et al. in 1964 dashed that hope with decisive evidence for CP violation. Accounting for this in the context of the two-family standard theory proved difficult, but theorists and experimentalists soon came to the rescue.

In 1973, even before there was any direct evidence for charm, the Japanese theorists Kobayashi and Maskawa showed how CP violation can result from complex Higgs coupling constants, but only if there are more than four quark flavors. At the time, few physicists believed the charm hypothesis, but convincing evidence for the fourth quark soon appeared and was quickly followed by the discoveries of a third charged lepton and a fifth *"bottom"* quark. These particles fit neatly into a third family of quarks and leptons, with all of its members since discovered. Physicists were as ready and willing to believe in a third fermion family as they were reluctant to accept the second, but they had to wait until 1998 for the surprisingly heavy *"top"* quark to show itself. The GIM mechanism was immediately and trivially extended to a system of three quark doublets. Complex Higgs couplings offer a correct description of all observed CP violating phenomena.

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[1] Glashow, Iliopoulos, Maiani

It is both good news and bad news that no confirmed departure from the predictions of the three-family standard theory has been observed. With its development many of the mysteries of the microworld have been solved, but some old puzzles persist and many new ones have arisen. Can they be successfully addressed? Or, as advocates of the string landscape propose, are they simply accidents of the birth of our particular universe?

vii. Cosmic microwave background

The discovery of the cosmic microwave background established the hot big bang conjecture and initiated the dramatic development of today's science of quantitative cosmology, but what does this have to do with the electroweak theory?

The background radiation tells us that the temperature of the universe is now about 3°C. The universe was about a thousand times hotter when the cosmic radiation was emitted, and far hotter earlier on. When it was at a critical temperature of about a trillion degrees, the electroweak symmetry was exact and unbroken. This phase transition is analogous to the melting of a crystal or the demagnetization of a heated ferromagnet, where complete rotational symmetry is restored above a critical temperature. For a tiny fraction of a second early in its infancy, when the universe was inconceivably hot, all of the gauge bosons, quarks and leptons of the Standard Model *(Figure 2)* were massless. Some physicists, suspect an even greater symmetry to manifest itself at yet higher temperatures, thereby exhibiting a grand unification of strong, weak, electromagnetic and perhaps even gravitational forces. The dream of a truly unified theory of physics shall never die.

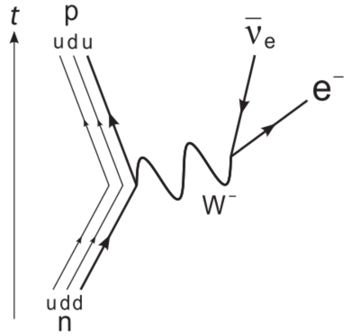

Figure 1: Inter alia, the weak force is responsible for radio-activity. This Feynman diagram illustrates a neutron (an up-quark and two down-quarks) transitioning into a proton (two up-quarks and a down-quark) via the emission of a W^- boson which transitions into an electron and an electron-antineutrino.

Courtesy WikipediaCommons.

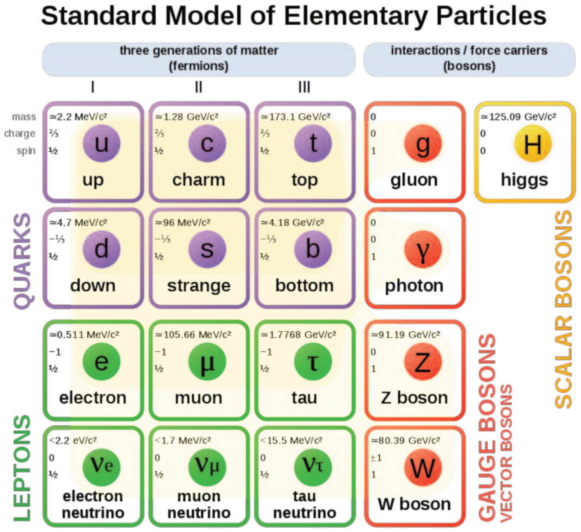

Figure 2: Standard Model of Particle Physics

Courtesy of WikipediaCommons.

Visit to CERN

By**David Forfar, MA, FFA, FRSE (Trustee of the Maxwell Foundation)**

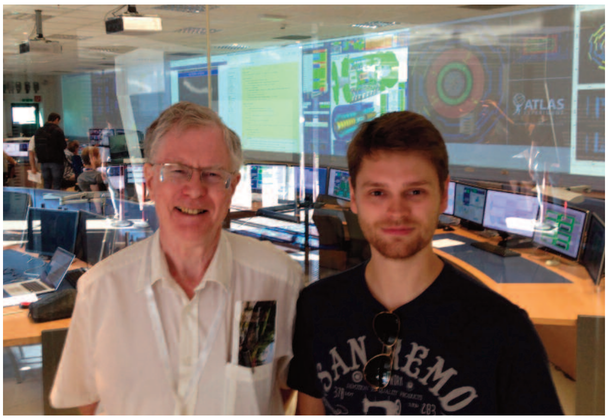

Figure 3 : ATLAS control room. Author with Edinburgh PhD student Matt Heath. Image Credit: Prof. Robson

In September 2018, as a past-chairman of the Clerk Maxwell Foundation, I was fortunate to visit CERN (*Organisation européenne pour la recherche nucléaire*) in Geneva and to be shown round by Professor Aidan Robson (Glasgow University and a friend of the Maxwell Foundation) and two of his research students (*Figure 3*).

CERN was created in 1954 with the mandate of establishing, in Europe, a world-class fundamental physics research organisation to enhance our understanding of the structure of matter. There are now twenty-two states which are members of CERN, around 2,500 CERN staff members including physicists and engineers and another 12,000 or more employed across the world in analysing the voluminous data output of CERN.

CERN's area of research is the study of the fundamental constituents of matter and the forces acting between them. Many new discoveries have been made at CERN, for example, the discovery, in 1983, of the carriers of the weak nuclear force which are the W^+ boson, the W^- boson and the Z boson.

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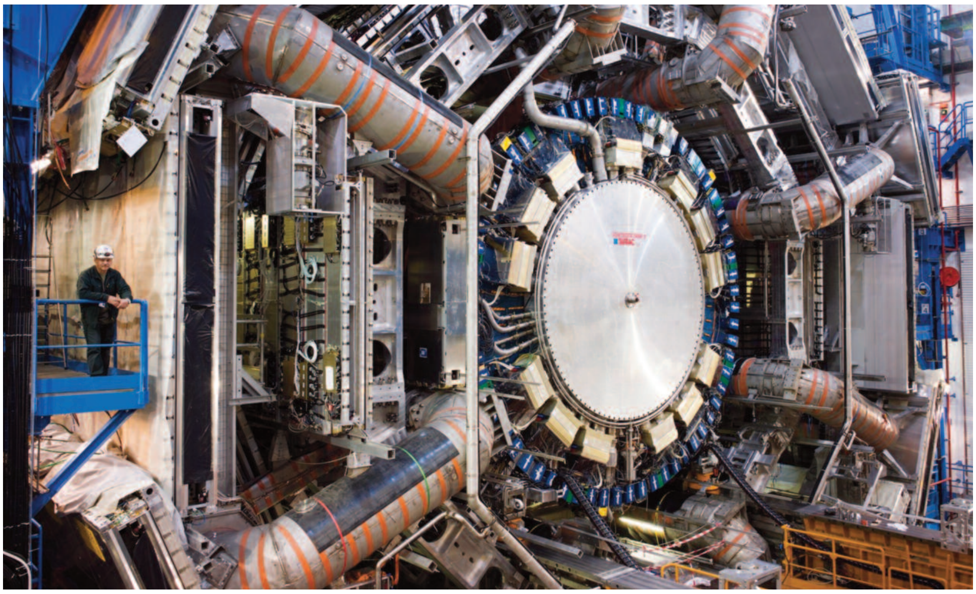

Figure 4 : ATLAS detector at the LHC.
Note, for comparison, the size of the man on the left. The ATLAS detector has the dimensions of a cylinder, 46m long, 25m in diameter, sits in a cavern 100m below ground and weighs 7,000 tonnes (similar to the weight of the Eiffel Tower). It is designed to detect some of the tiniest, yet most energetic, particles ever created on earth. A huge magnet system bends the paths of the charged particles into a circle. Beams of particles travelling at energies up to seven trillion electron-volts, or speeds up to 99.999999% that of light, collide at the centre of the ATLAS detector producing collision debris in the form of new particles which fly out in all directions. Over a billion particle interactions take place in the ATLAS detector every second. The detector tracks and identifies particles to investigate a wide range of physics, from the study of the Higgs boson and top quark to the search for extra dimensions and particles that could make up dark matter.

Image Credit: CERN

This followed the theoretical work of Professors Glashow, Salam and Weinberg on the unification of the weak nuclear force and Maxwell's electromagnetic force, culminating in their 1979 Nobel Prize (see above article by Professor Glashow):

"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current."

Professors Peter Higgs[2], Francois Englert and Robert Brout and others had, as early as 1964, proposed theoretically that what we mean by *particle mass* is the strength of the particle's interaction with a new type of field, now called the *Higgs field*. They proposed that during the expansion of the universe, very shortly after the big-bang (10^{-12} secs after!), when the temperature of the universe had dropped below a critical value, this field should emerge as having a non-zero value throughout the universe.

The Higgs field is quite different from other fields (for example, the magnetic field), which need a source (for example, a magnet) to produce them.

A mechanism, now called the Brout-Englert-Higgs mechanism, showed how, below the critical temperature, massless electroweak fields could mix to create the W^+, W^- and Z^0 bosons and the photon. This is the *spontaneous breaking of symmetry*. W and Z bosons have mass and mediate the weak force, which has very short range. The photon has no mass and mediates the electromotive force, which has long range.

Today, CERN is home of the world's most powerful particle accelerator, the *Large Hadron Collider* (LHC) *(Figure 4)*. Here a proton (a hadron) beam travelling at almost the speed of light collides with another proton beam travelling in the opposite direction. The resulting collisions create conditions similar to those at the start of the universe so our understanding of matter depends on the analysis of the particle debris resulting from the collision of the two proton beams.

Professor Higgs had also realised that, if the new type of field existed, then there should be *'ripples'* in it, which would be observed as a particle. Observing this particle, now called the *Higgs boson*, would provide evidence for this field.

In 2012, two separate experiments at CERN's Large Hadron Collider announced they had each observed, for the first time, a new particle with a mass of around 125 GeV/c^2. This particle was consistent with the Higgs boson. In 2013, the Nobel prize in physics was awarded jointly to Professors Higgs and Englert, Professor Brout having sadly died,

"...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."

Current research at CERN includes extending our understanding of the Higgs boson. Very recent measurements have observed the Higgs boson decaying to two bottom quarks as well as observing a Higgs boson being produced along with two top quarks or along with a W or Z boson.

The LHC detectors continue to look for unexpected experimental results that could be hints of physics beyond the Standard Model, such as dark matter or extra dimensions. To date, there has been no evidence of the existence of supersymmetric particles (an extension of the Standard Model).

Future colliders beyond the LHC are already being planned. One such proposal is for a new linear collider, the *Compact Linear Collider* (CLIC), which would collide electrons and positrons. Unlike protons, which contain quarks and gluons, electrons and positrons are (as far as we can tell) fundamental and indivisible, which allows certain measurements to be performed much more precisely.

Applications and 'spin-off' from the work of CERN have included the world-wide web as well as advances in medical diagnosis, high speed photography and computing as well as techniques to enable the handling of enormous quantities of data.

[2] Peter Higgs is the patron of the Clerk Maxwell Foundation

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