Electroweak unification

In order to explain certain features of radioactive beta decay, Wolfgang Pauli suggested in 1930 that the nucleus emitted, in addition to a beta particle, another particle of an entirely new type. The hypothesized particle, dubbed the neutrino, would not be discovered experimentally for another 25 years. It's not easy to detect neutrinos, because they respond to neither the EM force nor the strong force. For example, the mean free path (average penetration distance before it interacts) of a typical beta-decay neutrino moving through solid lead is about 1.5 light years! Enrico Fermi argued that neutrinos indicated a new force was at work. During the 1930s, he quickly adapted ideas from the developing new theory of QED to this new force, dubbed the weak force. Fermi's theory was able to predict the half-lives of beta-emitting nuclei and the range of energies of the emitted beta particles.

In 1967, Pakistani physicist Abdus Salam and U.S. physicist Steven Weinberg independently uncovered a connection between the weak force and the EM force. They proposed a new QFT that incorporated both the EM field and weak force field into a single “electroweak” force field and that incorporated electrons and neutrinos into a new electroweak matter field. This unification was comparable to the 19th-century unification of electricity and magnetism into a single EM field.

The electroweak theory is a broader version of QED. In this theory, the interactions of electrons, positrons, neutrinos, and anti-neutrinos arise from the exchange of photons along with three new types of exchange particles, labeled \( W^+ \), \( W^- \), and \( Z \). Unlike the photon, the \( W^\pm \) and \( Z \) have rest-mass, in fact surprisingly large masses of 86 and 98 proton masses, respectively. These large masses imply a short range for the weak force. Here’s why.

The whole QFT concept of forces due to (or “mediated by”) particle exchange is surprising, because strictly speaking it violates conservation of energy. It's an issue that arises even for two electrons interacting by the EM force. If the electrons are initially at rest, where does the energy for the exchange photons come from? This conundrum is more pressing in the case of the \( W^\pm \) and \( Z \) because they have large masses and thus (according to \( E = mc^2 \)) large energies. How can electrons or neutrinos create \( W^\pm \) or \( Z \) particles that are many times more massive than the electrons or neutrinos themselves? The resolution lies in the time-energy uncertainty principle \( \Delta E \Delta t \leq \hbar / 2 \pi \). This relation tells us that the energy of a quantum system can randomly increase or decrease by an amount \( \Delta E \) so long as it does so only for a time \( \Delta t \) that satisfies the inequality. These energy fluctuations violate conservation of energy, but only for a short time. Particles (field quanta) that arise from energy fluctuations and thus violate energy conservation can exist only for a limited time are called “virtual particles.” All exchange particles are virtual particles of this sort. Since there’s no lower bound on photon energies, \( \Delta t \) for exchange photons can be arbitrarily long and so the EM force has infinite range. But the masses of the \( W^\pm \) and \( Z \) imply that the force they mediate, the weak force, has a range of only \( 10^{-17} \) m, about 1% of the diameter of a proton. This short range is one reason neutrinos are so hard to detect.

Since the electroweak theory binds electrons and neutrinos into a single family, and since there are three generations of electrons, we might guess that there are also three generations of neutrinos. This would be a good guess. Unsurprisingly, they are called the electron-neutrino, the muon-neutrino, and the tau-neutrino. Table I shows the entire setup.

The strong force

Observations to date are consistent with electrons and neutrinos being point particles. That is, their force fields appear to be centered on a single point that itself takes up no volume. (Note however that their matter fields always occupy a spatial region of nonzero size \( \Delta x \), which can be compressed to arbitrarily small size only at the expense of a very large \( \Delta p \).)

But protons and neutrons are different. It’s been known since the 1950s that their charge is spread out over a tiny “fuzzball” region about \( 10^{-15} \) m across. In 1967, Richard Taylor, Jerome Friedman, and Henry Kendall used Stanford University’s linear electron accelerator to probe this fuzzball by shooting electrons at protons. Some of the electrons scattered quite strongly, revealing that the proton was not simply a uniform smear of matter. Later that year, theoretical analysis by James Bjorken suggested that this scattering could result from point-like constituents within the proton. Earlier, in 1964, Murray Gell-Mann and George Zweig had independently suggested the existence of a few simpler entities, dubbed “quarks” by Gell-Mann, out of which protons and neutrons could be built. But the connection between the experimental results and quarks was tenuous and eight more years of experimental and theoretical probing at several high-energy physics labs was required before quarks could be confirmed as physically real point-like constituents of protons and neutrons. The entire episode recalls Rutherford’s 1911 discovery of a tiny nucleus deep within what had been supposed to be a fuzzball atom. ^2

Are quarks, then, truly fundamental—not made of still smaller particles? We don’t know. Experiments to be conducted at the Large Hadron Collider proton accelerator near
to the electron field) that is quantized is the strong matter field. The quanta of the strong force field (analogous to photons) are called "gluons" because their exchange by quarks "glues" quarks together. On a larger scale, gluon exchange between quarks in different nucleons binds the nucleus together. Like the photon, gluons have no rest-mass. The quanta of the strong matter field are quarks of two types, called u-quarks and d-quarks (and their antiparticles). The theory predicts that there are two stable configurations of u- and d-quarks, namely the proton made of two u-quarks and one d-quark, and the neutron made of one u-quark and two d-quarks.

Whereas the electroweak fields of Table I participate only in the electroweak force and the gravitational force, the strong fields participate in every known force: strong, electroweak, and gravitational. Surprisingly, quarks turn out to be fractionally charged, the u possessing +2/3 of a proton's charge and the d possessing -1/3 of a proton's charge, adding up to a net charge of +1 for the proton and 0 for the neutron. So the positive charge of the atomic nucleus, and thus atomic binding and chemistry, stems ultimately from quarks. Quarks also participate in the weak force aspect of the electroweak force, for example in nuclear beta decay where one of a neutron's down quarks decays into an up quark with the emission of a beta particle (an electron) and an electron-antineutrino. Thus transforming the neutron into a proton.

There's an important difference between the way gluons relate to the strong force and the way photons relate to the electric force: Gluons exert and feel the strong force, while photons do not exert or feel the EM force. In other words, gluons can create and destroy gluons, unlike photons, which cannot create and destroy photons. This explains one of the most curious features of quarks: As two quarks are pulled farther and farther apart, the greater distance means that the exchange gluons have more time to create additional gluons, implying a rapidly increasing energy in the strong force field. Past a certain point, this energy buildup becomes large enough to create a new quark-antiquark pair. If, for example, you pull one of a proton's u-quarks away, there's a buildup of gluons flying between the u-quark and the remaining u+d. As you pull further, eventually a u+anti-u pair is created, of which the new u joins the u+d to again form a proton, and the anti-u joins the u that you were trying to remove, to become an unstable quark-antiquark pair. It's a beautifully crazy explanation of why years of searching for isolated quarks never succeeded.

Protons have a rest mass of 938.272 MeV/c^2. That is, the proton's energy at rest is 938.272 MeV; when converted to joules and divided by c^2, this gives the proton's mass in kilograms. But the masses of the u-quark and d-quark are 2.01 MeV/c^2 and 4.79 MeV/c^2, respectively, so the total mass of a proton's three quarks is only 8.81 MeV/c^2. The other 929.46 MeV/c^2 of a proton's mass comes from the energy of the strong force field that binds protons together. So about 99% of the mass of ordinary matter comes from field energy. It's a terrific example of Einstein's mass-energy relation and illustrates that everything is made of fields.

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Table I. The theory of the electroweak force. Two fundamental electroweak fields pervade the universe: an electroweak force field whose quanta are the four exchange particles listed, and an electroweak matter field whose quanta are the electron and the electron-neutrino. In addition, there are second-generation and third-generation matter fields whose quanta are listed.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Particle Type</th>
<th>Mass (proton=1)</th>
<th>Charge (proton=+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>electron</td>
<td>0.0005a</td>
<td>-1</td>
</tr>
<tr>
<td>1</td>
<td>electron-neutrino</td>
<td>a</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>muon (mu electron)</td>
<td>0.11a</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>muon-neutrino</td>
<td>a</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>tau (tau electron)</td>
<td>1.90</td>
<td>-1</td>
</tr>
<tr>
<td>3</td>
<td>tau-neutrino</td>
<td>a</td>
<td>0</td>
</tr>
</tbody>
</table>

**Exchange particles:**
- photon: 0 (0)
- W^+: 86 (1)
- W^-: 86 (-1)
- Z: 98 (0)

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Table II. The theory of the strong force. Throughout the universe there is a strong force field whose quanta are gluons and a strong matter field whose quanta are u-quarks and d-quarks. Protons are made of u-u-d, and neutrons of u-d-d, bound together by the strong force acting between quarks. In addition, there are second-generation and third-generation matter fields whose quanta are listed. Only the first-generation quanta are stable and play a role in ordinary matter. The second and third generation decayed during the early moments of the big bang and exist today only during brief high-energy microscopic events.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Particle Type</th>
<th>Mass (proton=1)</th>
<th>Charge (proton=+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>u-quark</td>
<td>0.00214</td>
<td>+2/3</td>
</tr>
<tr>
<td>1</td>
<td>d-quark</td>
<td>0.00510</td>
<td>-1/3</td>
</tr>
<tr>
<td>2</td>
<td>c-quark</td>
<td>1.4</td>
<td>+2/3</td>
</tr>
<tr>
<td>2</td>
<td>s-quark</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>3</td>
<td>l-quark</td>
<td>185</td>
<td>+2/3</td>
</tr>
<tr>
<td>3</td>
<td>b-quark</td>
<td>5.0</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**Exchange particles:**
- gluons (8 types) 0 (0)

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Geneva will penetrate to new depths of smallness and could discover that quarks, too, are composites.

With the discovery of quarks, physicists developed a version of QFT that describes the interactions between quarks and agrees with all experiments designed so far to test it. In this theory, the strong force (also called the "color force") acts directly between quarks, and the attractive force acting between protons and neutrons is a consequence only of the strong force acting between their quarks. The force field (analogous to the EM field of QED) that is quantized in this theory is the strong force field, and the matter field (analogous to the electron field) that is quantized is the strong matter field. The quanta of the strong force field (analogous to photons) are called "gluons" because their exchange by quarks "glues" quarks together. On a larger scale, gluon exchange between quarks in different nucleons binds the nucleus together. Like the photon, gluons have no rest-mass. The quanta of the strong matter field are quarks of two types, called u-quarks and d-quarks (and their antiparticles). The theory predicts that there are two stable configurations of u- and d-quarks, namely the proton made of two u-quarks and one d-quark, and the neutron made of one u-quark and two d-quarks.

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Table II shows the entire strong force setup. Notice the many parallels between Tables I and II: The three-generational structure of the electroweak theory is preserved in the theory of the strong force, with each generation comprising a pair of matter particles. In Table II, the second and third generation each consist of two quarks that are heavier and unstable variations on the stable u- and d-quarks, much as the muon and tau are heavier and unstable variations on the electron. In addition, each table has several kinds of exchange particles or force particles, including photons and gluons moving at speed $c$. This similarity between Tables I and II points to a close connection between the two forces, suggesting that there should be a “grand unified theory” combining all the fundamental forces except gravity. But such a theory still eludes science’s grasp, as does a “theory of everything” that would include gravity.

In its present stage of development, the QFTs of the electroweak and strong forces, as summarized in Tables I and II, are called the “standard model,” a boring title for a theory with such fantastic predictions and unerring accuracy. Amazingly, this theory accommodates all subatomic phenomena observed so far. The Large Hadron Collider is designed to reach beyond the standard model. Stay tuned.

Acknowledgments
I thank my University of Arkansas colleague Michael Lieber, and Rodney Brooks of Wanaka, New Zealand, for useful discussions. I thank my three referees for their helpful critique.

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