Is a Grand Theory of Everything Finally within Reach?

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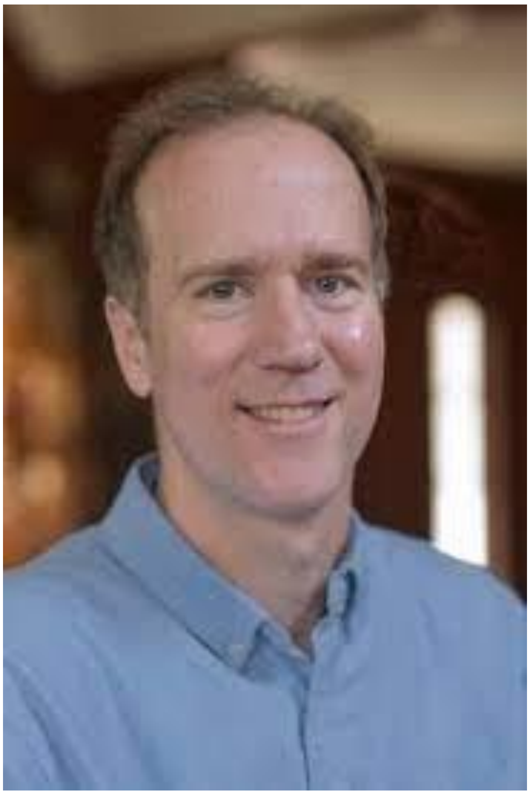

When trying to explain what motivates me as a physicist, the film *A Passage to India* (1984) comes to mind. Based on the play by Santha Rama Rau, adapted from the novel by E M Forster, it describes the fallout from a rape case in the fictional city of Chandrapore, during the British Raj in India in the 1920s. What keeps the viewer's attention is the subtlety of the relationships between the characters – particularly the fragile friendship between the man accused of the rape, Dr Aziz, and an Englishman, Mr Fielding. Data about identity alone, such as race, class, gender or educational status, can never reveal these dynamics nor capture why they fascinate us. When the case arrives in court, ostensibly similar people behave very differently in relation to the defendant. The dynamics of individual behaviour trump any immutable labels we might apply; yet these static labels also impose constraints on just how far any individual can go. We watch, we theorise, and we update our knowledge of the characters and the forces at work. By the end, we find that Fielding and Aziz are more alike than we'd thought, having created a new bond on the basis of a more complete understanding of one another.

Curiosity

The curiosity that drives many particle physicists isn't so different from what keeps us watching *A Passage to India*. The obvious and immutable data about the identity of elementary particles include their spins, their electric charges and their masses. From muons to charms, we can learn such information pretty quickly. But it takes years, even lifetimes, to reveal both the nature and degree of their relationships.

The neutrino, for example, was introduced in 1930 by Wolfgang Pauli, who needed to account for the fact that energy was conserved when a nucleus broke apart. But he would never have guessed how deep the relationship is between a left-handed spinning electron and the neutrino. It took more than 40 years of careful observations and ingenious theoretical work to reveal the deeper unified relationship they have together: via the fundamental force we now know as the 'weak force'. That's where the deepest and most satisfying learning in particle physics is to be found: through painstaking observations and the sifting of evidence comes a creative willingness to allow for multiple possibilities.

With the discovery of the Higgs boson in 2012, every elementary particle predicted by the Standard Model of physics has now been found. Yet the field is far from 'done'. Among the continuing work, physicists are still looking for a grand unified theory that explains the forces that operate at the subatomic level – a common understanding that accounts for the disparate phenomena we observe among the particles we have in hand. Not everyone agrees that this is worthwhile or even possible; some think we finished learning new things about elementary particles in 2012, and we must accept the cacophony of unrelated details in our physics tables. But I believe that to understand nature at its foundations, it's necessary to push further, to unearth more subtle and surprising relationships beneath the surface of what we see.

Unification of Subatomic Forces

Our observations to date support the idea that a unified theory of subatomic forces can be achieved. If true, it would revolutionise our understanding of nature far beyond any discovery of particle physics in the past half century – akin to theological transitions from polytheistic religion (many deities, many fundamental forces) to a monotheistic religion (one unified God, one unified force).

Unification revelations – 'they are more like each other than we thought' – have been remarkably productive throughout science. We now know that nature is often simpler and more cohesive than it seems. For most of human history, our theories for why planets move was disconnected from beliefs about why boulders tumble down mountains and apples fall off trees. But in 1687, Isaac Newton revealed that gravity offered a single, unifying explanation. All the explanations that had one 'force' for planets wandering in the sky, and another for apples being pulled to the ground, were brought together in one economical framework.

Other odd forces revealed themselves to us, but good explanations were slow to arrive. Between his duties attending to the medical needs of Queen Elizabeth I and her court, the physician and physicist William Gilbert wrote his magnum opus *De Magnete* at the start of the 17th century on the forces and attractions of electric charges that explained the workings of a compass. But the challenge of how to reconcile electrical charges with magnetic attraction and repulsion fascinated and confused natural philosophers for centuries thereafter. The crowning achievement came in 1861, when James Clerk Maxwell unveiled a set of equations that put electricity and magnetism on equal footing. The theory of electromagnetism showed that they were 'more alike than you think'.

Newton's Gravitational Conundrum

However, a conundrum remained in Newton's theory of gravity and his laws of motion. The mass of a particle that's used in equations to predict the particle's acceleration when subject to *any* force (electromagnetic force, gravitational force, force due to a spring, etc) is mysteriously exactly the same mass that's used in different equations to determine what gravitational force exists between the particle and some other body. The first kind of mass is called the 'inertial mass' and the second kind 'gravitational mass'. Newton had to arbitrarily assume their exact equivalence to get the correct answers, even though there was no compelling reason why it had to be so.

However, Albert Einstein's general theory of relativity solved this mystery by theorising that there's a single unified origin for both types of masses. Einstein recognised that the feeling of total weightlessness when you're in freefall, even in the presence of gravity, is because of the equivalence of your inertial and gravitational masses. He elevated this observation to the *principle of equivalence*. In an acclaimed review article on relativity in 1907, he concluded that any new gravitational theory that included his new concepts had to conform with the principle of equivalence. It was this idea that ultimately helped him complete the formulation of the general theory of relativity in 1915.

What's so interesting about the principle of equivalence, from our point of view, is that it could just as easily be called the *principle of mass unification*. What led Einstein to general relativity were thoughts of unifying disparate objects (these masses are 'more alike than you think'), which in the old theory had no reason to be connected to each other. Newton unified planetary orbits and apple falls; Maxwell unified electricity and magnetism; and Einstein unified inertial mass and gravitational mass.

What new frontier can we identify in nature that calls out for deeper understanding of the relationships between particles – a new principle in the tradition of unifying planetary orbits with falling apples, electricity with magnetism, and inertial mass with gravitation? A good answer is a tighter relationship between elementary particles through the unification of certain forces that determine their interactions, known as the *gauge forces*. These three forces are electromagnetism, the weak force, and the strong force.

Gauge Bosons

With these three forces come many *gauge bosons* – a fancy way of describing the particles that are exchanged in order to activate the forces. There are a total of 12 such gauge bosons, or force carriers, in the Standard Model. There is one electromagnetic gauge boson (the photon) associated with the electromagnetic gauge force, three weak gauge bosons (W+, W-, Z) associated with the weak gauge force, and eight strong-force gauge bosons (the gluons) associated with the strong gauge force.

The electromagnetic force is mediated by photons, which get exchanged between particles that feel electric attractions and repulsions. The weak gauge force is what causes many particles to decay into others. For example, a neutron will spontaneously fall apart into three new particles: a proton, an electron and an antineutrino. We didn't understand exactly how this decay could happen. After all, neither the neutron nor the neutrino have an electric charge, so they can't talk to each other via photon exchange of the electromagnetic force.

Now, what if all three of the gauge forces were to be unified into a grand unified force – a single Ur-force? What would the observational consequences of such a reality be? For one, the relative charges of each particle under all three gauge-forces would have to follow a very particular pattern consistent with what a grand unified force would require. Secondly, the strength of each of the three forces would need to converge to a unified strength as we go to higher energies. Third, there would be new particles beyond those we have already seen. And finally, there would be decays and interactions among known particles that are forced on us, even at low energies, by the grand unified theory. Our observations to date push us in the direction of entertaining the existence of an Ur-theory of nature.

Likewise, we can analyse more particles in the Standard Model, such as right-handed electrons, right-handed up quarks and left-handed up and down quarks. After many measurements, we find another set of willy-nilly values for the charges they display under all three gauge-forces. But upon closer inspection using group theory mathematics, we find that those numbers also magically fit exactly into a single grand unified particle: W= (right-handed electron, left-handed down quark, right-handed and left-handed up quarks). It's as though 10 very raggedy puzzle pieces scattered on the floor were pieced together to make a perfect circle.

Unification as Nature's Choice

It didn't have to be this way. The charges of the elementary particles in our Universe could have been such that there was no way to unify any two or more of them into a single unified particle. It's the combination of observational data and mathematics that offers us strong hints that the charges for elementary particles in the standard model aren't arbitrary, but rather arise by virtue of being embedded into a grand unified theory framework.

There's a second set of observational data hinting that the unification of the gauge forces is nature's choice. This comes from measuring the strengths of the forces. When we measure the strength of the electromagnetic interaction and compare it with, say, the strong interaction, we get a very different answer.

Again, it didn't have to be like this. One of the force strengths could have moved away from the pack as we moved up the energy scale. This would have immediately made the project of grand unification look impossible or highly suspect. Furthermore, the scale of putative unification adds to the positive view of this picture. Its value is neither too low to run up against the problem of proton decay (to be discussed below), nor is it too high (10^{17} or higher) to collude with the inscrutable dynamics of strong gravity that spoils all calculations and interpretations. We see again that observational data (force strength measurements) and theoretical work (group theory and renormalisation group techniques) have led us toward grand unification.

Is there any way to obtain direct proof of unification? What I've described so far count as strong hints, but by no means are they proof. They could be cruel coincidences of nature that have led us astray. To obtain 'proof for all practical purposes' would require us to do experiments at the unification scale and observe the production of new particles and new interactions directly through collisions.

For example, many grand unified theory ideas require the existence of an additional grand unified gauge boson that could be directly produced in collisions, seen, and measured. Unfortunately, it's out of the question to build a high-energy collider that could reach the energies where we think the grand unified theory resides. It took us many decades to reach energies of only a few thousand times the proton mass – and it might never be the case that experiments could reach energies of 15 orders of magnitude higher, which is what it would take to convince the most ardent sceptics.

Proton Decay

The search for a grand theory isn't over, though. One of the most sought-after hints is the data connected to the search for proton decay. Along with the neutron, the proton makes up the nuclei within our bodies. If the proton were to decay quickly, it would disrupt our cells and give us cancer and we could never have reliable life. Fortunately, the proton lives a very long time: as far as we know, it lives for at least 10^{34} years. That's about 24 orders of magnitude longer than the lifetime of the Universe. The prediction of grand unified theories for the lifetime of the proton generally falls in the range of 10^{30} to 10^{36} years. Any theories that predict a proton lifetime of less than 10^{34} years can be ruled out.

It's vital for us to find and catalogue the particles that serve as nature's raw material. But if we stop there, we're like impatient school children who merely read the Wikipedia synopsis of *A Passage to India* and then get on with writing their term papers. There's so much more to learn and to synthesise about this complex narrative than the basic facts reveal. The story of nature is all the more woven with an infinite number of patterns, most as yet unseen. The subtle relationships between particles – the interactions between themselves in many different environments – is what lends our understanding its richness. The revelations of unification in science in general, and especially in physics, have been incredibly fruitful in the deepening of our knowledge and in lighting the way to future discoveries.

Among the many possibilities for unification, nature seems to have dropped us irresistible hints that our particles and our gauge forces are indeed unified into a grand unified theory of some kind. These hints are based on observational data along with the advanced theoretical tools of relativistic quantum field theory and group theory mathematics. However, the limitations of our technology have also made it extremely hard for us to get more direct proof. Seeing a proton decay is one of our few hopes for more direct corroboration – and that's why so much effort is going into watching protons with an eagle eye to see if one disintegrates. Data will determine whether unified theories will continue to pay off as they have for so many centuries. If history is our guide, we have every reason to believe they will.*

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