The Grand Design
Chapter 5. **The Theory of** Everything

by Professors **Stephen Hawking** and **Leonard Mlodinow**

The known forces of nature can be divided into four classes:

1. **Gravity.** This is the weakest of the four, but it is a long-range force and acts on everything in the universe as an attraction. This means that for large bodies the gravitational forces all add up and can dominate over all other forces.

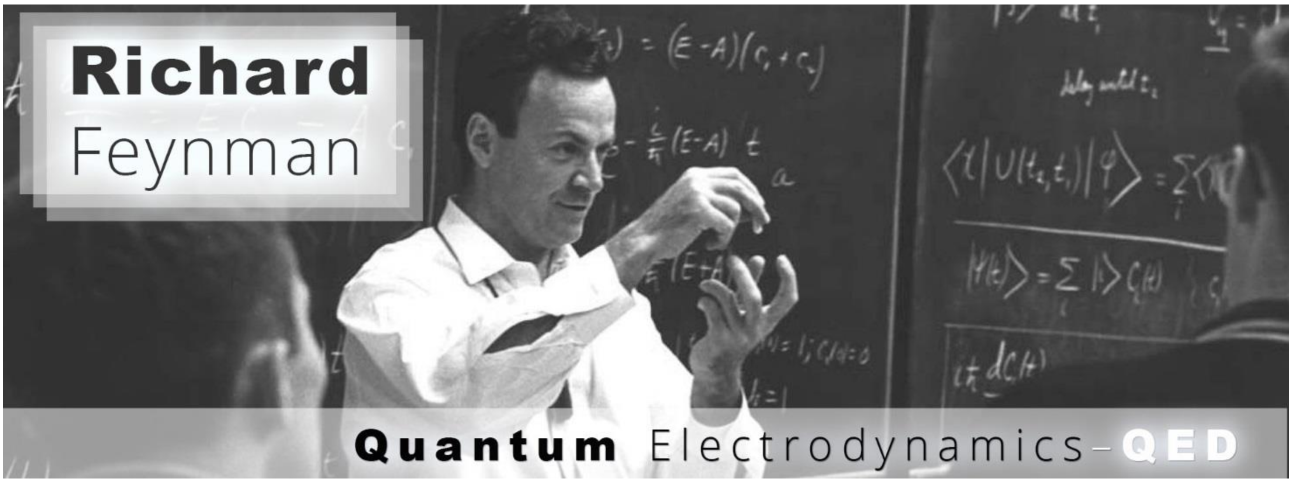
2. **Electromagnetism.** This is also long-range and is much stronger than gravity, but it acts only on particles with an electric charge, being repulsive between charges of the same sign and attractive between charges of the opposite sign. This means the electric forces between large bodies cancel each other out, but on the scales of atoms and molecules, they dominate. Electromagnetic forces are responsible for all of chemistry and biology.

3. **Weak Nuclear Force.** This causes radioactivity and plays a vital role in the formation of the elements in stars and the early universe. We don't, however, come into contact with this force in our everyday lives.

4. **Strong Nuclear Force.** This force holds together the protons and neutrons inside the nucleus of an atom. It also holds together the protons and neutrons themselves, which is necessary because they are made of still tinier particles; quarks. The strong force is the energy source for the sun and nuclear power, but, as with the weak force, we don't have direct contact with it.

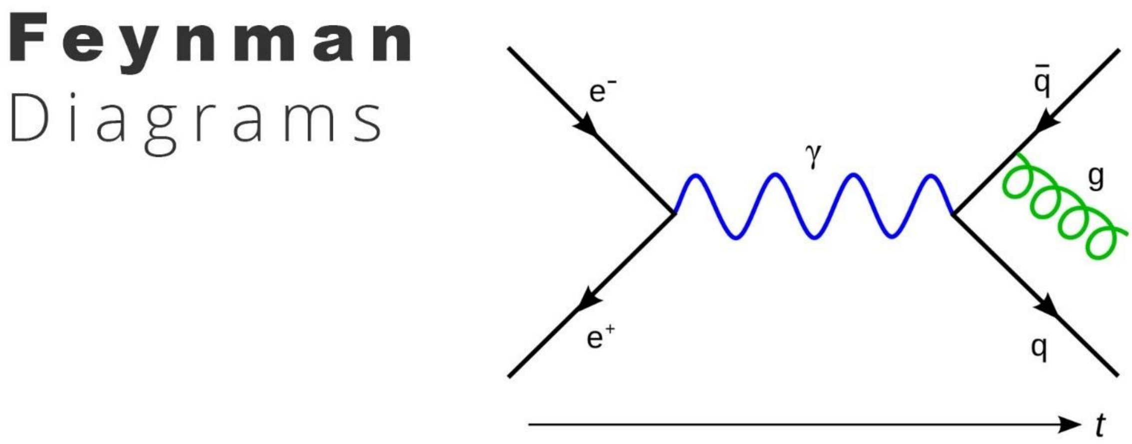
The first force for which a quantum version was created was electromagnetism. The quantum theory of the electromagnetic field called quantum electrodynamics, or QED for short, was developed in the 1940s by Richard Feynman and others and has become a model for all quantum field theories.

A particle of light is an example of a boson. According to QED, all the interactions between charged particles—particles that feel the electromagnetic force—are described in terms of the exchange of photons.



The predictions of QED have been tested and found to match experimental results with great precision. But performing the mathematical calculations required by QED can be difficult. The problem, as we'll see below, is that when you add to the above framework of particle exchange the quantum requirement that one include all the histories by which an interaction can occur—for example, all the ways the force particles can be exchanged—the mathematics becomes complicated. Fortunately, along with inventing the notion of alternative histories—Feynman also developed a neat graphical method of accounting for the different histories, a method that is today applied not just to QED but to all quantum field theories.

Feynman's graphical method provides a way of visualizing each term in the sum over histories. Those pictures, called **Feynman diagrams**, are one of the most important tools of modern physics. **In QED the sum over all possible histories can be represented as a sum over Feynman diagrams.**



The process of renormalization involves subtracting quantities that are defined to be infinite and negative in such a way that, with careful mathematical accounting, the sum of the negative infinite values and the positive infinite values that arise in the theory almost cancel out, leaving a small remainder, the finite observed values of mass and charge.

Once we have fixed the mass and charge of the electron in this manner, we can employ QED to make many other very precise predictions, which all agree extremely closely with observation, **so renormalization is one of the essential ingredients of QED.**

The success of renormalization in QED encouraged attempts to look for quantum field theories describing the other three forces of nature. People have therefore sought **a theory of everything** that will unify the four classes into a single law that is compatible with quantum theory. This would be the holy grail of physics.

The strong force can be renormalized on its own in a theory called QCD, or quantum chromodynamics. Since earlier observational evidence had also failed to support GUTs (Grand Unified Theories), most physicists adopted an ad hoc theory called the standard model, The standard model is very successful and agrees with all current observational evidence, but it is ultimately unsatisfactory because it does not include gravity.

The **closed loops** in the Feynman diagrams for gravity produce infinities that cannot be absorbed by renormalization because in general relativity there are not enough renormalizable parameters (such as the values of mass and charge) to remove all the quantum infinities from the theory. We are therefore left with a theory of gravity that predicts that certain quantities, such as the curvature of space-time, are infinite, which is no way to run a habitable universe. That means the only possibility of obtaining a sensible theory would be for all the infinities to somehow cancel, without resorting to renormalization.

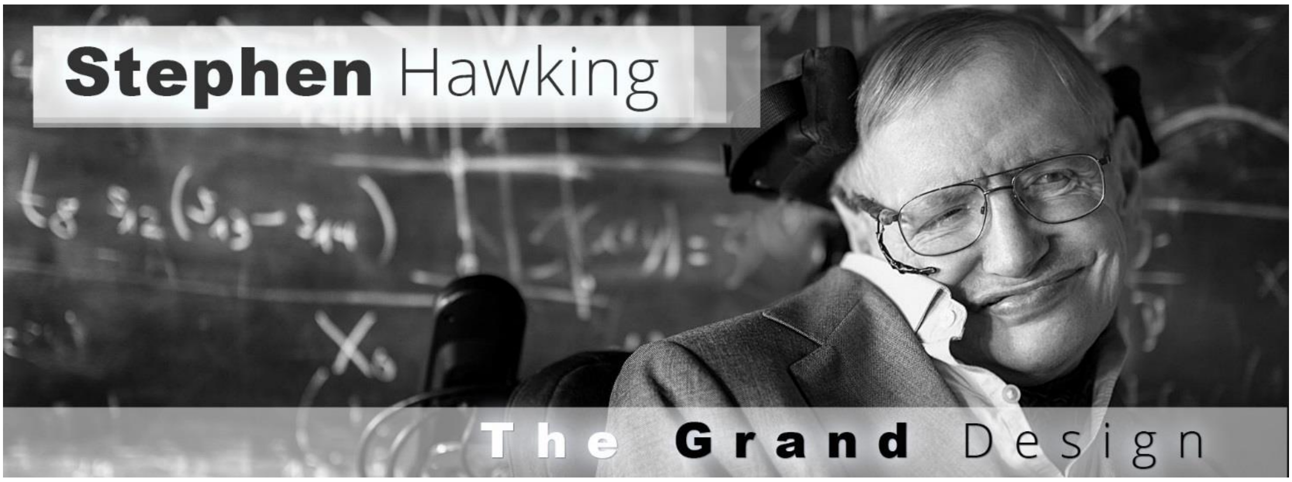
In 1976 a possible solution to that problem was found. It is called supergravity. **The prefix "super" was not appended because physicists thought it was "super"** that this theory of quantum gravity might actually work. Instead, **"super" refers to a kind of symmetry the theory possesses, called supersymmetry.**

In physics a system is said to have a symmetry if its properties are unaffected by a certain transformation such as rotating it in space or taking its mirror image.

One of the important implications of supersymmetry is that force particles and matter particles, and hence force and matter, are really just two facets of the same thing. Practically speaking, that means that each matter particle, such as a quark, ought to have a partner particle that is a force particle, and each force particle, such as the photon, ought to have a partner particle that is a matter particle. This has the potential to solve the problem of infinities because it turns out that **the infinities from closed loops of force particles are positive while the infinities from closed loops of matter particles are negative**, so the infinities in the theory arising from the force particles and their partner matter particles tend to cancel out.

The idea of **supersymmetry** was the key to the creation of supergravity, but the concept had actually originated years earlier with theorists studying a fledgeling theory called **string theory.** String theories also lead to infinities, but it is believed that in the right version they will all cancel out. They have another unusual feature: They are consistent only if space-time has ten dimensions.

Then, around 1994, people started to discover dualities—that different string theories, and different ways of curling up the extra dimensions, are simply different ways of describing the same phenomena in four dimensions. Moreover, they found that supergravity is also related to the other theories in this way. String theorists are now convinced that the five different string theories and supergravity are just different approximations to a more fundamental theory, each valid in different situations.



That theory is called M-theory. No one seems to know what the "M" stands for, but it may be "master," "miracle," "matrix, "or "mystery." It seems to be all four. People are still trying to decipher the nature of M-theory, but that may not be possible. It could be that the physicist's traditional expectation of a single theory of nature is untenable, and there exists no single formulation. **It might be that to describe the universe, we have to employ different theories in different situations.** Each theory may have its own version of reality, but according to model-dependent realism, **that is acceptable so long as the theories agree in their predictions whenever they overlap,** that is, whenever they can both be applied.

Whether M-theory exists as a single formulation or only as a network, we do know some of its properties. First, M-theory has eleven spacetime dimensions, not ten.

The mathematics of the theory restricts the manner in which the dimensions of the internal space can be curled. **The exact shape of the internal space determines both the values of physical constants, such as the charge of the electron, and the nature of the interactions between elementary particles.**

In other words, it determines the apparent laws of nature. We say “apparent” because we mean the laws that we observe in our universe—the laws of the four forces, and the parameters such as mass and charge that characterize the elementary particles.

But the more fundamental laws are those of M-theory.”

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