The Big Questions
Spring 2008

Lecture Notes 6: Towards a Theory of Everything

1 A Brief History of Physics

For thousands of years, people have observed the world around them and asked the very simple question, “Why?” Why does an apple fall down from a tree? Why is the sky at night dark? And why does it hurt when a person punches me in the face? (. . . actually, why does it hurt a *lot*?)

For a long time, people didn’t make a whole lot of progress on these sorts of questions. The types of answers that people gave were, for a long time, philosophical or religious answers that we today would find to be quite unsatisfying. However, it was finally in the 1600s that Sir Isaac Newton — the English physicist and mathematician — gave a scientific basis to many of these fundamental questions about the Universe. He developed his famous 3 laws of motion, as well as his law of gravity, and with these laws he was able to explain why an apple falls down from a tree, as well as how all the planets in the solar system orbit the Sun. It was completely remarkable! Science was changed forever.

The next major revolution occurred in the 1800s, when the Scottish physicist James Clerk Maxwell explained how electricity and magnetism work. In fact, he actually *unified* electricity and magnetism into a single object known as “electromagnetism.”

Moving forward into the 1900s, there were essentially two major revolutions in physics. The first was Einstein’s theory of relativity. He figured out special relativity in 1905 and then it took him another 10 years to figure out the general theory. Relativity, recall, is essentially a theory of space and time. In fact, like Maxwell, Einstein *unified* space and time and showed how the *correct* way to think about space and time is not separately but rather as different aspects of a single *spacetime*. In *Lecture Notes 5*, I talked a bit about relativity and some of its weird consequences — moving clocks run slow, moving sticks get shorter, mass bends space and time, *etc.*

The other half centered around the branch of physics known as *quantum mechanics*. Quantum mechanics is the theory that has proven to be enormously successful in explaining the very small — atoms, electrons, protons, and so forth. I talked a *little* bit about quantum mechanics when I talked about parallel universes, in particular, the Level III multiverse (see *Lecture Notes 3*). In these notes, I'll just say a few words.

According to quantum mechanics, the way you describe all the objects in the Universe is by using what's called the *quantum state*. The quantum state is very different from the *classical* state — the state of non-quantum physics, like relativity or the physics of Newton. In non-quantum physics, you can completely specify the state of an object by saying its location and speed. Now, it may be that you have a hard time figuring out the object's location and speed, but you can rest assured that the object certainly *has* one.

In quantum mechanics, the situation is utterly different. Objects *no longer* have definite positions and speeds. What they *do* have is a thing called a "superposition," which is sort of a mixture of a variety of positions and speeds. It's only when you make a measurement on an object that the object will have a definite position or speed. This is called the "collapse" of the quantum state. It's very weird... I know.

Now here's the catch. Before you make a measurement on an object — like measuring its position, say — you have no way of knowing with certainty what you'll measure. You can predict with some *probability* what you'll measure, but it's impossible even in principle to know for sure. So there's a fundamental *random* aspect to quantum mechanics. This underlies the famous "uncertainty principle" of quantum mechanics.

2 Quantum Gravity

Since relativity and quantum mechanics were proposed, they've passed every experimental and observational test put forth towards them. No experiment or observation has ever contradicted the predictions of quantum mechanics or relativity. So they've both been wonderful success stories.

Unfortunately, we now know that they *can't possibly be right*. It turns out that, when we look at the two theories — when we look at the equations of the two theories, which I'm obviously not going to show you — we find that they actually *contradict* each other and even give nonsensical answers to some questions. For example, when you try to combine the two theories in a straightforward way to answer a simple question like, "What is the probability that a certain event happens?" you can get an answer like an infinite probability! Which of course doesn't make any sense at all, since probabilities must range from zero to one.

At a conceptual level, it all comes down to the fact that, deep down, everything in Nature fluctuates according to quantum mechanics, including spacetime itself. However, in general relativity, spacetime is a *fixed, rigid* thing that does not fluctuate. So, when you try to combine the two theories, you're bound to run into some problems, which is exactly what happens.

So we have a big problem here. We have a fundamental conflict between our two best theories of Nature. So it seems that we need a *new* theory to explain quantum effects and gravity; we need a theory of *quantum gravity.*

I should say from the outset that *nobody* in the world knows what the correct theory of quantum gravity is. However, many theoretical physicists today are working to discover what that theory is. Probably the most promising theory — certainly the most popular theory today, anyway — that people are working on is *string theory.* So I'll focus on string theory in these notes and then say a few words about other theories.

3 String Theory

According to string theory, everything in the Universe — every person, every atom, every electron, every proton, and so forth — is made up of *extremely* tiny objects called "strings." These strings are many, many times smaller than the size of the atom, but they have properties that are similar to the kinds of strings that we all know and love. For example, consider a rubber band. Rubber bands are *closed* strings because they close on themselves to make a circle, but you can turn them into *open* strings just by snipping them with a pair of scissors. The strings of string theory have similar properties to these everyday strings; for example, the strings of string theory can either be "open" or "closed."

As another example, suppose you took a string and stretched it. You'd feel an inward force; the rubber band would try to go back to its original shape — this is called "tension." The strings of string theory also have a kind of "tension."

Now here is the truly remarkable thing about string theory. We all know that, for everyday strings, depending on how you stretch the string, you'll hear different musical notes — different pitches — when you pluck at it. In other words, different ways that you vibrate the string give rise to different musical notes.

In string theory, the different ways that the *fundamental* strings vibrate actually give rise to the different types of particles that you find in Nature. For example, if a string vibrates in one way, it can give rise to an electron, whereas if it vibrates in another way, it can give rise to a proton, or some other kind of particle. So string theory has a very elegant way of explaining the wide diversity of all the fundamental particles that have been observed in Nature. Particle physicists have observed about 30 fundamental particles, yet for a long time they had no idea why these particles exist. String theory gives a very elegant answer: these particles are simply the result of different ways that strings vibrate.

How does this solve the problem of quantum gravity? Well, it turns out that one of the string's vibrational patterns has precisely the properties needed to be the particle that transmits the force of gravity — this particle is often known as the *graviton*.

Let me back-track a little bit. You all know about the gravitational force, which every object that has mass experiences. You've probably also heard about the electromagnetic force, the force of electricity and magnetism. These are two fundamental forces of Nature that we know about. We actually know of two other fundamental forces in addition to these — the forces present inside the atomic nucleus. There's one force, called the *strong nuclear force*, which is responsible for holding the nucleus of the atom together. And there's another one, called the *weak nuclear force*, which is responsible for radioactivity and how certain particles decay.

Now, according to modern particle physics, each of these forces has what's called a "force carrier," a messenger particle sent out by a particle which tells other particles how to interact with it. So, you might have an electron here, for example, and a proton there, and the proton might send out a messenger particle of the electromagnetic force, and then this particle would essentially "tell" the electron to attract it (opposite charges attract). Similar things would happen with gravity and the other forces.

An amazing thing about string theory is that, if you carefully analyze the equations of the theory, then you discover that each of these messenger particles simply *pops out* of the equations. So, string theory isn't just a quantum theory of gravity; it's also a quantum theory of electromagnetism, the strong nuclear force, and the weak nuclear force. So, string theory actually *unifies* all of the known fundamental forces in a single theory. It's because of this that people have referred to string theory as a potential "theory of everything."

Now, it turns out that you can only *get* these results — you can only have a consistent "theory of everything" — if you have a certain number of dimensions of space. We're all familiar with the usual 3 dimensions of space — you can move left and right, forward and backward, and up and down. According to the most modern versions of string theory, you actually need *ten* spatial dimensions for the theory to make sense at all. When you look at the equations of string theory, they *demand* that you have 10 dimensions of space.

If you're human at all, this should sound very strange to you! After all, it doesn't *seem* like there are more than 3 dimensions, so how can this be? Well, there are at least 2 possibilities. The first is that these extra dimensions are *curled up*. For example, consider a water bottle. From far away, it looks like it only has one dimension, a dimension moving from left to right. However, if you look at the bottle more closely, you see that there's another dimension — a dimension which goes *around it*. The extra dimensions of string theory could be of this kind. They would have to be *extremely* small, but in principle they would be there — all around us.

Another possibility concerning these extra dimensions is that they're just like the familiar 3 that we know, but our existence is confined to a small portion of space — we're stuck on a 3-dimensional slice of space (called a *D-brane*). This is similar to how things would be for a 2-dimensional being living on a 2-dimensional sheet of paper. We humans know that the sheet of paper really lives in 3-D space, but a creature living on the 2-D sheet would only perceive 2 dimensions. Analogously, we only perceive 3 dimensions when in reality there may be 7 others.

And it could actually be that the right answer is a combination of the two — curled up dimensions plus D-branes. Nobody really knows. In fact, there are many basic questions about string theory that nobody knows the answer to. For example, by the 1990s, people had discovered 5 different *versions* of string theory. People suspected that perhaps one of them was right, but they didn't know which. It was then *showed*, by a physicist named Edward Witten, that these 5 theories are actually all related to each other and might therefore be different aspects of a more fundamental theory. This theory has been called *M-theory*. (The "M" could stand for master, mystery, magic, or matrix, depending on your preference.)

Nobody knows all the details about this M-theory, but many theoretical physicists around the world are currently working on it today. But the real test of any theory — the real test that determines whether a theory is *any good at all* — is to compare predictions of the theory with experiment. Quantum mechanics and relativity, for instance, have passed all the experimental tests perfectly. The situation with string theory, unfortunately, is a bit difficult. Because the basic objects of string theory — the strings themselves — are extremely tiny, this makes them extremely difficult to detect and therefore difficult to test the theory

Nevertheless, there *is* an aspect of string theory that physicists are excited to test very soon, known as "supersymmetry." Supersymmetry is a kind of symmetry between particles. There are two kinds of particles in nature — "fermions" and "bosons." Fermions are the types of particles that electrons and protons are. Bosons are the kinds of particles that the force carriers are. The distinguishing feature between bosons and fermions is a property called "spin," which unfortunately I can't really get into, but it's a built-in kind of angular momentum (*i.e.*, spin) that all particles have. A theory is supersymmetric if it says that, for every boson there is a corresponding fermion with all the properties of that boson, except that it has the spin of a fermion.

String theory is a supersymmetric theory, so it predicts that every particle has a supersymmetric partner. This summer, a new particle accelerator in Geneva, Switzerland — called CERN — will begin operating. It's going to be the most powerful particle accelerator in the world. And one of the things it's going to search for is supersymmetry. So, if it finds supersymmetry, that would be good news for string theory. If it doesn't, then that's not so good news for string theory, and physicists would have to think harder about the proper description of Nature.

4 Alternatives to String Theory

Until now, I've focused on one possible theory of quantum gravity that people have proposed — string theory. But there are people in the world working on other theories of quantum gravity. Probably the biggest competitor to string theory today is what's called *loop quantum gravity.* To explain this theory, I should probably finally say what the word "quantum" means, which you may have been wondering about. "Quantum" simply means "the smallest unit of something." For example, suppose you took some matter and chopped in half. Then you took one half, and cut that in half. And then you cut that half in half, and so on. Would you be able to keep doing this forever?

Well, you've all heard of atoms, so you all know that matter comes in fundamental little pieces. And, of course, atoms are made up of protons, neutrons, and electrons, so even atoms can be broken up. And it even turns out that protons and neutrons are made up of even smaller pieces called "quarks." But physicists believe that quarks are truly fundamental — elementary — and so are electrons. So matter comes in small, fundamental chunks. In other words, matter comes in quanta. A quark is a quantum of matter, and an electron is another quantum of matter.

In loop quantum gravity, spacetime itself is comes in quanta. There is a smallest unit of space and there is a smallest unit of time, according to the theory. If you kept probing space deeper and deeper, you'd eventually arrive at a smallest unit. And if you had a super-watch, you'd be able to see that time is actually digital as opposed to analog, according to loop quantum gravity. And the great thing (its proponents say) is that this seems to be able to reconcile the differences between quantum mechanics and general relativity.

But, like string theory, loop quantum gravity currently has no experimental support, simply because the theory's quanta of space and time are too small to measure by today's technology. The quantum of volume is about 10^{-99} cm^3 and the quantum of time is about 10^{-43} seconds.

There are other theories of quantum gravity that people have proposed: some approaches include things called semiclassical gravity, twistor theory, Bohmian approaches, and causal sets. Unfortunately, nobody knows what the right theory is.

But it's important to keep an open mind and to remember that, ultimately, experiment is the determining factor of whether a theory's any good. We don't know what the theory of quantum gravity is today, but many people feel we're getting pretty close. In fact, many people believe it's quite possible that, in our own lifetime, we will finally have the "theory of everything." And perhaps that theory will be simple enough to put on a T-shirt.