PROFESSOR: So I'd like to begin today by clarifying something I talked about at the end of last class.

OK, so last week I was talking about time travel in general. And at the end of last class, I was talking about time travel to the past. I talked about this method that some people have thought of that might work, possibly, using what's called wormholes.

And remember a wormhole is a path, a shortcut between points in space time, that the equations of general relativity just allowed to exist. It's this weird thing that the equations just allow to exist.

So a supposed space is two-dimensional. It's not really two-dimensional, but I just want to draw some kind of picture. Let's suppose you're looking at it from this view. Oh, attendance, OK.

Suppose you're looking at it from this view, then it would look like that. Now a wormhole would connect two regions like this. Now they can just travel from one region to the next by traveling through a wormhole. It would be a shortcut.

Now a student asked after class last week. So, OK, this is space, and this is the wormhole, but what's this? What is this in-between space? Is it some kind of extra dimension, like a fourth dimension of space, or some kind of a hyperspace thing? The answer is no.

This is actually nothing. I just needed a way to draw space being curved on the board. I needed a way to connect two points in space, and this was the only way I could think of doing it. So as a result, I got this extra stuff that looks like it's actually something, which isn't.

It's not an actual dimension of space. It's just an artifact of the way that I drew things. It's not actually anything. General relativity doesn't need an extra dimension of space to have wormholes. It's weird enough to get the job done in three dimensions.

Does anybody have any questions about wormholes or time travel? Any questions from last week? Yeah.

AUDIENCE: Is space [INAUDIBLE]?

PROFESSOR: Well, space is three-dimensional, time is one-dimensional. So spacetime is three plus one, four-dimensional.

AUDIENCE: How do you [? draw that? ?]

PROFESSOR: How do you draw that? You can't. [LAUGHS] I mean, I can draw something that's supposed to give you an idea of what it could be. I mean, I don't know of any way of drawing it in an adequate way. Any way that you draw it, it's always going to have some defects. Like here you have this extra stuff, which isn't really anything. There's no good way of drawing it.

I mean ultimately you have to sit down and look at the equations. I'm not going to show you the equations. And if you want, you can completely disregard this equation on my shirt, if it distracts you.

But yeah, this is just a defect of the way that I drew things. It's actually similar it's actually similar to what happened when I talked about the expanding universe. Remember the way I described it was to imagine that the universe is like the surface of the balloon. And then you inflate the balloon, you blow up the balloon. So the balloon becomes bigger.

As a result, the points on the balloon move away from each other. The distances between the points increase. And that's what we mean by the expansion of space. The universe isn't expanding into anything. There's nothing. The universe just is. It's not expanding into anything. When I say that the universe is expanding, all that I mean is that the distances between points increases. That's all that expanding means.

But we want to have some way of visualizing it, and this is an easy way of visualizing it. But it makes you think that space is expanding into something, which it isn't. That's just a defect of the way that we drew things. Question.

AUDIENCE: If the universe is like a balloon, will it blow up?

PROFESSOR: If the universe is like a balloon, will it blow up? No. See, that's another defect of the way that I describe things. The only way it's like a balloon is that points on the surface of the balloon move away from each other, and points in the universe move away from each other.

It could also be the case that it has a geometry like a balloon. That's another way, it could be closed. It could be finite and closed. That's another way. But the notion of blowing up or popping, those are just defects of the way that we use to describe it.

Although, remember, it doesn't even look like the universe is like a balloon. It looks like it's actually infinite and flat in a certain sense.

AUDIENCE: [INAUDIBLE]

PROFESSOR: Just like the way that they thought the Earth was flat? Yeah, kind of like that. OK, now, so general relativity doesn't require there to be extra dimensions of space. Right? It can get the job done in three dimensions of space.

But that's not to say that extra dimensions of space don't exist. I'm just saying that general relativity doesn't require them. And actually later, later, I'll talk about the very real possibility that there are extra dimensions in space when I talk about string theory.

But the general relativity itself doesn't require there to be extra dimensions. And so if you add another dimension, you just add extra stuff to the theory. You make it more complicated.

So why should you add extra stuff? Why should you make the theory more complicated?

This actually raises an interesting point in the philosophy of scientific theories. Before I get to that are there any questions about this?

OK, the profound point that I was alluding to in the philosophy of science is it has to do with the simplicity of theories. In general, when scientists go about making theories, they generally want the one that's the simplest. The simpler the theory, the better.

And this is called Occam's Razor.

Occam was just a philosopher that was around 700 years ago or something like that. [LAUGHS] So the simpler the theory, the better. And this sounds reasonable, right?

It's something that we use in everyday life when we try to come up with an explanation of something. I mean suppose somebody just walked in and was trying to explain the observation that there are a bunch of students in this room.

Why are there these students in this room? A very simple explanation is that about six weeks ago, or a little bit more than that, looked at the class list for this program at MIT called HSSP, saw an interesting class at 1:30 to 3:30 PM every Sunday, and so you decided to take it.

Then you've been coming here for the past six weeks. And today's no different from all those other Sundays, and so you came here. That's a very simple explanation for why you're here. It's probably the most natural one that we would think of.

But you can think of other explanations. You can think of crazier explanations. Here's another one. It could be that all of you guys are very special in a certain way. And you're here because-- [LAUGHS] Sorry.

You're here because wizards thought that you should be here, because in the very far future, something drastic will happen to the world. And you guys are special in a certain way that you can save the world.

And having knowledge of big questions will help you save the world, something like that. And so you're here, because the wizards manipulated your mind in giving you the illusion of wanting to be here, and then you're just here for all the Sundays, because the wizards made you here. Something like that.

Just to think of a random explanation. And sure that sounds crazy, or silly, or whatever, because it's more complicated than the explanation that I gave just before, which is that you're, because you're excited to be here. And you've come here every Sunday, and so you're here today.

So this rule that we use is pretty reasonable. We use it in everyday life. Simpler explanations are better than more complicated explanations. But why should this be the case? Why should simpler theories be better? Why should the best theory be the simplest theory?

Can anybody actually give an explanation for that? A justification for this Occam's razor? Yeah?

AUDIENCE: Because it was simpler and easier to prove.

PROFESSOR: It was simpler and maybe easier to prove? Why might it be easier to prove if it's simpler?

AUDIENCE: Because [INAUDIBLE] really complicated, then it's easier to make a mistake with it.

PROFESSOR: So, yeah, if you have a complicated theory, then you have to have everything just right. There might be a lot of steps in the explanation. If one goes wrong, then the whole explanation's wrong. Whereas with a simple explanation, you only have a few number of steps.

You just need a few them to come right. You just need a few of them to be right. Yeah, I think that's kind of the gist of the explanation that I've heard, at least the best explanation I've heard. Any other explanations for this? For the explanation?

So probably the best justification I've heard goes as follows. So every physical theory has some fundamental-- I'm just going to make your argument a little more precise. So every physical theory has some fundamental principles, some fundamental postulates.

Now remember last week I talked about relativity. Special relativity has these two postulates. The first is that the laws of physics are the same for all observers that are moving at a constant velocity. And at the speed of light, it's the same for all observers moving at constant velocity.

Those are the two fundamental postulates of special relativity. They can't be provable. They're just fundamental. And all the consequences of the theory derive from those postulates.

Every theory has some fundamental postulates. But it's impossible to know if they're actually true. You can perform a number of experiments, and we've certainly done experiments around special relativity, for example. And experiments might be consistent with those postulates every single time. But it could be that, deep down, the postulates-- it's not that they're wrong, per se.

It could be that the postulates are incomplete in some kind of a way. It could be that nature is just fooling us. That we're not really seeing the true nature of nature. It could be that the postulates are just incomplete.

So every physical theory has postulates, and every postulate has some amount of uncertainty associated with it. I mean, you could be wrong about the postulate. Now the justification for Occam's razor, at least the best one that I've heard, says, let's suppose that every postulate has a set amount of uncertainty.

Every postulate of every physical theory has the same amount of uncertainty. So the more postulates that you have in a theory, the more uncertainty. Now the more postulates that you have, the more complicated you make your theory, the less simple you make your theory. So therefore, the simplest theory has the fewest number of postulates, and, therefore, has the least amount of uncertainty.

So the less uncertain you are in the theory, the more likely the theory is of being right. And so the simpler the theory, the better. Where better means having the greatest chance of being right. So I think that's kind of a reasonable argument. I mean it's not perfect, but it's kind of reasonable.

There are other justifications that people give for this Occam's razor. For example, I mean nature-- I don't really like the other ones. I mean a lot of-- one of them is an aesthetic reason. I mean nature has to be simple. It has to be elegant. It has to be beautiful. I think the one that I gave was probably the best one.

[LAUGHS]

OK, are there any questions about Occam's razor, about how that works? OK, so I'd like to continue along these lines of thinking about theories, the theory that describes nature. Last week I talked about relativity. A few weeks before when I talked about parallel universes, I mentioned quantum mechanics. And today I'd like to talk about the theory of everything.

I mean we want to understand everything. We want to have some kind of a picture of the way the universe works. We want to have a theory. We want to be able to predict things and then manipulate nature. So we need a theory of everything. I mean if we really want to understand everything, we need a theory of everything.

Now before I talk about the theory of everything

[MUSIC ECHOING IN THE DISTANCE]

OK, that was interesting. The theory of everything is beautiful as you can see. Before I talk about everything, I'd like to give just a brief history of mankind's quest in coming up with the theory of everything. It's essentially a brief history of physics. Because then we'll be able to better appreciate, you'll be able to better appreciate the things that people are working on today and just how strange the theory of everything would have to be, and to better understand it.

I could start by saying, OK, this is what people think the theory of everything is. I could start like that, but I think I think it would be more enjoyable if I just give a brief history of physics. It won't take incredibly long.

For thousands of years, people have looked around, and we've observed things. We've asked why? Why this? Why does an apple fall down? Why is the sky dark? Why does it hurt when somebody punches me in the face? Why does it hurt a lot? And why do people have to do that?

[LAUGHS]

So for a long time people weren't really making a whole lot of progress on these sorts of questions. The types of answers that people would give would be pretty philosophical answers or religious answers that are not scientific answers. I mean a scientist today would not be satisfied with the answers that people gave for a very long time.

But finally this guy, Sir Isaac Newton comes along in the 1600s. And he explains a lot of things.

Newton came along, gave his three laws of motion, that you've all probably heard. He also gave his law of gravity. And with these laws, he was able to explain a lot. He was able to explain why the apple falls down and hits you in the head. Why the Earth revolves around the Sun, why the Moon revolves around the Earth, why all the planets revolve around suns. A lot of stuff.

The next revolution in physics happened in about the 1800s. Newton was probably-- physics was probably defined by Newton. Or put into its modern form by Newton. It was completely remarkable.

Probably the next revolution in physics came about in the 1800s with Maxwell

[CHANTING ENTHUSIASTICALLY]

Yeah, Circle of Life, circle of physics. In the 1800s, somebody called James Clerk Maxwell came along and explained electricity and magnetism. We're all familiar with electricity, magnets, and that sort of thing. Maxwell actually showed that electricity and magnetism are unified.

They're actually two sides of the same coin of electromagnetism.

Turns out that an electric, as an electric field changes, a magnetic field is produced, and as a magnetic field changed, an electric field was produced. And there's this deep connection between electricity and magnetism. And the best way of thinking of them is thinking of them as a unified object called electromagnetism.

And so by 1900, people had explained pretty much all everyday phenomena. You can use Newton's laws of motion to describe how things, how everyday objects move around, how things fall, how things push each other, how things pull each other. You can explain the stars, how they orbit through gravity.

You can also explain a wide variety of electrical phenomena and magnetic phenomena. So pretty much all everyday phenomena were figured out by 1900s. People thought, people actually thought back then that they had finally come up with the theory of everything. And that the next task, the remaining task for physicists was just to figure out some of the constants a little better.

For example, there's this constant called the gravitational constant that determines how strong gravity is. It's a number, and physicists thought at the time, that number's like the gravitational constants and other constants just needed to be determined more accurately. And that's all that was remaining for physics. So physics was solved by the 1900s.

But it turns out that Newton's theory and Maxwell's theory actually are at odds with each other. They're actually inconsistent with each other. So either one of them, or both of them had to be false. Can anybody guess which one turns out winning, or if or if any of them turned out winning?

Who thinks Newton was right? One for Newton. Who thinks Maxwell was right? One point, one, two, three, four, five, 5.5-ish for Maxwell. Yeah, it turned Maxwell's electromagnetism was the right theory. It's not that Newton was wrong. He wasn't wrong. It was just incomplete. It turns out that Newton's laws just worked for things moving at small speeds.

Once things start moving at high speeds, you need Einstein's theory of relativity. So in the early 1900s, Einstein essentially showed how to fix Newton's laws. I mean Newton's laws actually, I mean Newton's theory actually comes out as a limiting case of relativity. And Einstein showed that.

So 1905, Einstein proposed the special theory of relativity.

[SCRIBBLES]

The theory with two postulates, and it basically solved this discrepancy between Newton and Maxwell. Last week I talked about some of the consequences of special relativity. For example, I talked about time dilation, the fact that clocks that are in motion go slow. I also mentioned length contraction. A moving stick is slower than one standing still.

I also mentioned that simultaneity is relative. The fact that if I observe two things happening at the same time like [SNAPS] both of my fingers snapping at the same time. That doesn't necessarily mean that you will. If you're moving at some speed relative to me, it might not happen at the same time. Simultaneity is also relative, so everything is relative. Well, a lot of things are relative. But the speed of light, you remember, is not relative. The speed of light is the same for everybody. But anyway that was the special theory of relativity, which I talked about last time. Then about 10 years later, 10 years or so later, Einstein came up with his general theory of relativity.

[CHANTING LOUDLY]

[SCRIBBLING ON CHALK BOARD]

And that was the theory of gravity remember. Special relativity does not take into account things that accelerate. It doesn't work for accelerated observers, and it can't explain gravity. But general relativity can explain gravity. And, in fact, it's a better theory of gravity than Newton's law of gravity. And you remember in relativity, space and time are unified as a fundamental object called spacetime.

They're linked to each other. Whereas according to Newton, time and space are separate things. They're absolute. According to Newton, if I measure the duration of a song to be three minutes, then everybody will measure that song to be three minutes long. But according to Einstein, if you're moving at some speed relative to me, then maybe you'll measure it to be shorter, or perhaps, longer.

I imagined it to be three minutes, yeah, then it would be longer. That song would be longer, because time would be slowed for me. Remember my clock will tick slower to a moving observer. And so, therefore, it takes it takes longer for the stationary observer for the whole song to finish. So time is relative-- time is not absolute in Einstein's theory of relativity and neither is space.

So that's relativity. That was the first half of the physics revolution that happened in the 20th century. In the 1920s, there was another revolution in physics that happened. And this was the development of quantum mechanics, which is the theory that describes the very small. It's the theory that's been enormously successful in explaining the very small, atoms, protons, neutrons, electrons, very small.

This was developed in 1920S, so, there wasn't just one guy associated with quantum mechanics. It was a number of people, people like Erwin Schrodinger,

[WRITING]

Werner Heisenberg, and other than other people. And this was in the 1920s.

Schrodinger from Schrodinger's cat, remember you put the cat in the box and put the radioactive poison in there. They developed the quantum mechanics.

[SQUEAKING]

I mentioned quantum mechanics briefly when I talked about parallel universes. In particular, the level three multiverse where the parallel universe, in that case, corresponded to the many worlds interpretation of quantum mechanics.

Now I'll just I'll just briefly remind you of some of the things about quantum mechanics. I'm not going to try to do justice to quantum mechanics, but I'll just say a few essential things.

So according to quantum mechanics, there are objects in the universe, and each object has its states. Each object has quantum states. And this states they describe objects with is completely different from the states that you use in Newton's theory or Einstein's theory. It's completely different.

According to pre-quantum physics, the physics before quantum mechanics, the way you can describe an object is by using what's called the classical states.

The classical states is just an object's speed and position. If you know an object's speed and location, then you know everything about it. That's the classical state. The object has a speed. It has a location. Then you can learn it, and then you learn the classical state. It might be that you have a hard time determining what that state is.

You can have a hard time figuring out the speed, maybe it moves very fast, or maybe it's very small, you have a hard time figuring out the location. But you can rest assured that it definitely has a speed and position. That's something that we can all be happy with. That's the classical state.

The quantum state

[WRITING]

Is completely different from the classical state. Objects no longer have speeds and they no longer have positions.

[WRITING]

An object doesn't have a speed, it doesn't have a position. What it does have is some kind of a mixture between positions and speeds, and remember this is called the superposition. It does have superpositions.

And remember these were mixtures of states, mixtures of definite states. So while an electron might not have a speed. Just doesn't have a speed, doesn't have that property, or have a location. It does have a mixture of those. It has a mixture of definite speeds and definite locations, and that's called a superposition.

Now this is only true if you're not measuring the object. Once you measure the object, you give it a definite speed, or you give it a definite location. So an object doesn't have a speed, and it doesn't have a location until you measure it.

And the weird thing is that you never know what that speed or position is going to be until you make a measurement. You have no idea what it's going to be. You have an uncertainty in the future. There's a fundamental random aspect to nature that quantum mechanics gives the world.

You don't know with certainty what you're going to get in a measurement. You only know that you might get something or something else with some probability, and that's it. So that's the catch. It's very weird. Yeah, I know it's very weird, but that's the way that the world seems.

Quantum mechanics and relativity are both the two most successful physical theories that have ever been proposed. And we just have to live with their weirdness. We just have to live with them.

OK, now while every experiment and every observation has confirmed predictions of quantum mechanics or relativity with flying colors. I mean we can test these theories past the 10th decimal point. I mean we know that they're accurate-- we can make a prediction of something within 0.00000000-- approximately that many zeros and then a 1. That's how good it is. It's super accurate, super precise. They're pretty good theories, the best theories you've ever had to explain the world.

Unfortunately, we know that they can't possibly be right. They can't be right. They can't be completely right. And that's because when you look at the two theories, when you look at the equations that describe the two theories, you find that they contradict each other.

I mean deep down at a conceptual level, everything in quantum mechanics fluctuates. Remember there's a random aspect to the way that things changed. So things fluctuate. Things randomly fluctuate. They're called quantum fluctuations.

Now relativity is a theory of space and time. It's the theory of spacetime. Now if you want to make a quantum theory of spacetime, then spacetime should also fluctuate. That's a straightforward way of turning general relativity into a quantum theory. In a straightforward way of combining the theory, spacetime should also fluctuate. But according to general relativity spacetime is a fixed, rigid thing.

I mean it can change as-- spacetime can certainly change as with matter and energy, cause different geometries of the universe. Remember I talked about the curvature of spacetime. The more mass there is some place, the more curved it is. So spacetime can change that way. But there's an intrinsic way that spacetime can change that quantum mechanics says it must change.

But general relativity says it can't change like that. So you're bound to run into problems when you try to combine the two theories, and you do. That's exactly what happens. You run into problems when you try to combine the two theories. For example, if you ask, OK, suppose I try to measure something. Remember, quantum mechanics, you only have a probability that you measure something.

You don't know for certainty that you'll measure it. So you calculate the probability.

Probabilities are between zero and 100%, or between zero and one, so you should expect to get a number between zero and one when you calculate a probability. Well, when you try to combine quantum mechanics and general relativity, then you get infinite probabilities.

What's an infinite possibility? You get nonsensical answers. I mean a probability has to be-- it has to be between 0 and 1. So what's an infinite probability? It just doesn't make any sense. So our two theories, when you combine the two, they give nonsensical answers, even though by themselves, they make sense. And they describe experiments and observations well.

So we have a big problem here. We have this fundamental conflict. So it seems we need some kind of a new theory to describe nature, some kind of theory that combines elements of quantum theory and elements of general relativity. So we need a theory of quantum gravity.

[WRITING]

A quantum theory of gravity. Now I should say from the outset that nobody knows, nobody in the world knows what the correct theory of quantum gravity is. Nobody knows. But people have over the years tried to come up with theories. Theoretical physicists have worked on theories. And probably the most promising theory that people are currently working on is called string theory.

Maybe it's not the most promising, but at least it's the most popular theory that people are working on. And so for the rest of today I'll talk about string theory, and then I'll briefly talk a bit about some other theories that people are working on. Because its not the only theory that people are working on. But it's the most popular theory, and people think it's cool.

It's fun to talk about. I mean you've probably heard about it from TV specials, or newspapers, or whatever, because it's very strange. So I'll talk about that after the break.

So we'll take an early break today for five minutes, and then we'll reconvene.

OK so string theory is a theory of quantum gravity that people have proposed. It's probably the most popular theory that people are working on today. It seems like it's the most promising, but that's not for me to say. I'm not an expert. So according to string theory, everything is made up of extremely tiny objects called strings.

So calling it string theory, every object in the universe, every person, every atom, every proton, every electron, every quark, every photon, they're all made up of extremely tiny objects called strings.

These strings are many, many times smaller than atoms, but they have properties that are similar to the types of strings that we all know, everyday strings. For example, I can have an open string, like an open rubber band. I can stretch it. I can have-- I have, sorry, this is a closed string. Because it closes on itself. It's closed.

I can also have an open string like in everyday life. And in string theory, there are objects that are similar to everyday strings. They can be closed or open, similar to the sense that I just showed you. You can also stretch everyday strings. And once you stretch a string, it will pull back on itself. There's a tension. It pulls back, pulls back on itself. There's a tension.

The strings of string theory also have a tension. Now here's the remarkable thing about string theory. So for everyday strings, if I take it and I stretch in a certain way to produce a sound, depending on how I pluck it, I can get a different sound.

So depending on how I make the string vibrate, I can get a different musical note. That's just a simple thing that we've all observed before. If you haven't, then I feel sorry for those of you who have had childhoods deprived of rubber bands. Because they're a lot of fun to play with. You can learn a lot about the nature of reality by playing with rubber bands

[THRUMS]

Now with rubber bands and everyday strings, you can get different musical notes by stretching it and making the string vibrate in a certain way. With string theory, you can also have different kinds of vibration. You can have different modes of vibration. And in string theory, the different vibrations don't correspond to different musical notes, they correspond to different particles that we observe in the universe.

So one kind of vibration could lead to a proton. Another kind of vibration can lead to an electron, or another kind of vibration can lead to her--

[LAUGHS]

Well, many strings vibrating in a certain way, not just one. So string theory actually explains where all these particles come from. It explains a wide diversity of particles. Particle physicists have long observed a number of fundamental particles. There are about 60 of them. Or about half of them are anti-matter, so 30 fundamental particles in the universe.

And we just we just observe the stuff. We don't really know now where they come from. String theory has a very elegant answer to that question. String theory says that the particles are just different ways that fundamental strings vibrate. That's it.

So how does string theory solve the problem of quantum gravity? How does it reconcile quantum mechanics and relativity? Well, it turns out that the way some of these strings vibrate is the key.

So if a string vibrates in a certain way, you can actually get a graviton, which the particle that transmits the force of gravity. So let me let me just backtrack a little bit. So in particle physics, in modern particle physics, we have things called messenger particles. Or force carriers.

Gravity is a force that we've all heard of. Every object that has mass attracts every other object. You've all heard of electricity and magnetism, or the electromagnetic force. That's another force that we've heard of. So those are two forces in nature.

But it turns out if you try to explain everything that we've ever observed, you need two more forces in addition to those. So if you look inside the atomic nucleus, then you see protons and neutrons. And you might wonder why is the nucleus held together. After all protons are positively charged and positive charges repel each other.

That's something that's true. That's something that we learned from electricity and magnetism. You might wonder why are nuclei held together? They should repel from each other. Protons repel other protons. They're surely not attracted to neutrons. Neutrons don't have any charge at all. So why are nuclei held together?

Well, it turns out that there's another force, completely different from electromagnetism, completely different from gravity. I mean, yeah, sure, gravitationally, the protons and neutrons in the nuclei attract each other, but it's so small. Gravity is this is the weakest force. It's much weaker than electromagnetism. So gravity alone can't account for why nuclei are held together.

But it turns out that there's another force called the strong nuclear force that explains why nuclei are held together. There's this force called the strong nuclear force, and that's what it does. It turns out there's another nuclear force called the weak nuclear force. And that's responsible for radioactivity. It explains certain types of decay.

So there are four fundamental forces that we know about. There is gravity, electromagnetism, the strong nuclear force, actually-- OK, the strong nuclear force. And the weak nuclear force.

I guess this is kind of arranged in order of historical discovery. It turns out that the strong nuclear force is the strongest force of all these. Strong force is the strongest one. The second strongest is electromagnetism. The third strongest is the weak nuclear force, and the weakest, the fourth strongest, is gravity. These are the four fundamental forces of nature.

Now according to particle physics, each one of these forces is carried by a messenger particle. It's carried by some kind of messenger particle. So, for example, you can have an electron here. And a proton here. So electron and proton. And they're opposite charges, so they should attract each other.

Why do they attract each other? Well, it's because there's a messenger particle transmitted by one of them to another one. And essentially, it tells them to attract. It just tells them to attract. It gets sent from one to the other and says, suppose-- I mean one way of visualizing it, like a cartoonish way of visualizing it, for example, is that the proton sends a messenger particle to the electron and then tells the electron, hey, come this way.

It just tells it the instruction. It turns out that the messenger particle for electromagnetism is the photon. And this is the symbol that we give for a photon. So the messenger particle for electromagnetism is called the photon. It just tells charged particles what to do. Attract or repel. If this was an electron, the messenger particle would say repel.

There's also a messenger particle for the strong nuclear force. It's called a gluon. There are three messenger particles for the weak nuclear force. They're called W and Z bosons. And theoretically, there's a messenger particle for gravity, and it's called a graviton.

We've observed all of these. We observed all of these messenger particles. We've never actually observed a graviton. But in principle we'd like to think that they-- I mean they should exist. All these other forces transmit forces-- all these other forces transmit messenger particles, and we've observed them, but we haven't observed the graviton, simply because gravity is just so weak.

It's just so weak, so much weaker than all these other forces. But in principle it should exist. So that's the way that forces are transmitted between particles in our modern particle physics way of looking at forces. Now according to string theory, if you work through the equations, if you work through the different ways that things can vibrate, then it turns out that you get a graviton.

It just pops out. One mode of vibration corresponds to the graviton particle. And it has all the properties of being a graviton. It looks like a graviton. It feels like a graviton. Maybe it really is a graviton.

We also get a photon. And you get all the other messenger particles. It just pops out of the equations. So string theory is not only a quantum theory of gravity, not only does the gravitation pop out. But all these other forces pop out. So what, so what is there in the universe besides matter and forces? I mean that's pretty much it.

Are we thinking, in principle, to be described in terms of the two, matter and forces. Matter interacts in a certain way with forces. We're all made of matter. Right, we think things matter.

So string theory is a theory of everything, essentially. Matter, forces. So string theory is one candidate Theory of Everything that people have proposed. [INAUDIBLE]

Does anybody have any questions about how this is supposed to work out, how all these all these different forces just pop out of the equations?

AUDIENCE: [INAUDIBLE]

PROFESSOR: You can see them in a particle physics experiments. [LAUGHS] You just see them. I mean, usually, I mean, well, you see evidence of them. You form your theories. You form your particle physics theory. And if messenger particles exist, then you get this. You get this results. And you can measure the results of your particle physics experiments, and if it's consistent with the theory where messenger particles exist, then that's good evidence for that.

But we've actually we've actually directly observed these. We've directly observed those messenger particles. But often the way that they work is in a virtual way. They only exist for a very short amount of time. Then they disappear from existence. But we can actually observe them directly, too. But often we don't observe them directly. Usually we don't observe them directly.

But we've seen them, so they exist. We actually didn't see the W and Z bosons until the 1980s.

So I suppose, until the 1980s it could have been that, it could have been that the theory was wrong, and there weren't messenger particles. But finally the in the late 80s, we saw it. Yeah?

AUDIENCE: What's the Higgs boson?

PROFESSOR: The Higgs boson-- so a boson is a type of particle. I'll say more about bosons and fermions in five minutes or so. Higgs boson is not a messenger particle. It doesn't transmit these forces. But it's actually a particle required by the Standard Model of particle physics that's required for the theory to make any sense at all.

And it's actually what gives particles mass in a weird, complicated way. But there's a Higgs field that permeates all the universe, and there are Higgs particles that should exist. But we've never observed the Higgs particle. But all of our theory rests on the existence of the Higgs particle.

AUDIENCE: [INAUDIBLE]

PROFESSOR: Yeah, so the Large Hadron Collider, which is the most powerful particle accelerator ever, well, will be the most powerful particle accelerator ever and will hopefully start be operating maybe in a month, or two months, or three months. It's very soon. It's going to search for the Higgs. It's also going to search for a bunch of other stuff. In particular, the search for the Higgs and hopefully it will find it.

If it finds it, then that's exactly the missing piece of the Standard Model. The standard model is basically our accumulation of all of our particle physics knowledge ever. And actually, it doesn't actually take into account gravity. The Standard Model explains these three forces and all the particles that interact through these forces doesn't explain gravity.

So the Standard Model is not a theory of everything. But it needs the Higgs boson. And hopefully the LHC will find it.

So what was I saying? Oh yeah, I was asking if there was any questions.

OK, so string theory could be a theory of everything, because it explains all the particles and all the forces. Now it turns out, it turns out that for the theory to make sense at all, similar to the way for the Standard Model to make sense at all, you need a Higgs boson. For string theory to make any sense at all, for the equations to be consistent with each other, as a mathematical necessity to avoid contradiction, you need 10 dimensions of space.

[LAUGHTER]

You need 10 dimensions of space for the theory to make any sense at all. Now we're all familiar with three dimensions that we perceive in everyday life, forward, backward, left, right, up, down. We're all familiar with those. But string theory says that seven more should exist. So that sounds kind of weird.

So you have to make sense of it in some kind of way. The equations just say that this number pops up, 10. The number 10 pops up for the number of space dimensions you need. Now one way of having a universe with 10 spatial dimensions is by having three that are similar, the three that we ordinarily observe, and the other seven could be curled up.

So there are three that are normal. There are three normal dimensions. And the others are curled up in a sense. So to explain this. So imagine I have this long water bottle or this long tube.

I mean suppose it's, just look at it, this long tube. It's curled up. The surface of it is curled up. So the cross-section of it looks like this. That's closed. And when you look at it, when you look at it far away, you don't really see the extra dimension. You look at the tube from far away, it kind of looks flat. So you don't really notice the extra dimension.

It could be that the extra dimensions of space are similar to this. They're curled up like this. They would have to be enormously small, because we don't observe them. They'd have to be enormously small. This is one possibility. They could be curled up, or compactified, is the term that the theorists use. But in principle they can be very small and curled up, and we would never observe them, and then that would be totally fine.

Another way is that the other dimensions are like the dimensions that we know, but our existence is confined to a small portion of all of space. So it could be that we live on a brane, it's called. So that's possibility one, curled up dimensions.

Possibility two is called D-branes. So it's similar to this. So imagine that you're a two-dimensional creature, and you're living on a sheet of paper. Your existence is completely confined to the two-dimensional sheet of paper. But we the omniscient observer can look and say, aha, the sheet of paper actually lives inside a three dimensional space.

So the observer isn't actually seeing all of reality. String theory says that well, maybe our existence is like this. Maybe we live on D-branes. So that's what these things are called. Maybe we live on things called D-branes, which are similar to sheets of paper living in three-dimensional space. So these are Sheets living in higher dimensional space.

Brane, by the way, is an abbreviation of membrane. And D is just the first letter of our guy's name. Dirichlet was his name. What's his name?

[LAUGHS]

So it could be that we're just living on a sheet of, essentially, like a sheet of paper. And there's a whole lot of universe out there that we never see. Or maybe the other dimensions are curled up. Or maybe there's a combination of both of them. Nobody really knows today. It could be both of them. Are there any questions about the way the dimensions work?

OK, actually there-- I mean there's a lot of enthusiasm for string theory these days. But there are a lot of basic questions about string theory that nobody knows the answers to. I mean one of them is how do the dimensions work out, how does that all make sense. Another is just what really is the theory?

So by the mid-1990s, people had essentially discovered five different versions of string theory.

I mean they were all types of string theory, but they looked like they were fundamentally different from each other. But then it was noticed that they're all related to each other in a certain way by some kind of a transformation.

You can turn one of the theories into the other by applying some kind of transformation. So then the idea emerged that perhaps these five different versions of the theory are one aspect of an underlying fundamental theory. So you have string theory one, two, three, four, five. Maybe they're just different manifestations of some underlying structure.

Some underlying structure, yeah, similar to the way space and time, they look fundamentally different at first sight. But then when you think harder about it, they're actually just different manifestations of an underlying structure. And similar to the way that electricity and magnetism, they look different from first sight. But once you think harder about it, they're actually two different of the same coin.

So often in physics, we see two things that, or we see multiple things that look different from each other. But when you actually think harder about it, you realize they're not really different.

They're actually the same thing. They're just different sides of the same coin. So often in physics, unification occurs. Things get unified.

Electricity and magnetism were unified, space and time were unified. Well, maybe these five different versions of string theory are unified. And so this question mark indicates that fundamental theory, that foundational theory, that perhaps these five different versions of string theory are different manifestations of. And that theory has been come to known as M-theory.

Where M stands for magical, or matrix, or master, or mystery, depending on your preference. Nobody knows all the details about M-theory, but many people are working on it today. But the real test of any theory, the test that determines whether it's any good at all, is if it confirms with experiments.

Quantum mechanics, and special relativity, and general theory, they've all been confirmed by experiment. They've passed all tests with flying colors. But string theory has yet to be confirmed by experiments. Right now it's completely theory. It's purely mathematical. In fact, even the mathematical status of the string theory is questionable.

So the critics of string theory like to point out that it's not even wrong, because it hasn't even been tested yet. And the reason for that is that these strings, these fundamental strings, are just so small. You can't see them at all. You can't see them with today's technology. You probably won't see them with technology of 100 years from now or 200 years from now, maybe even 1,000 years from now.

So there's a big technological problem in testing string theory, which has caused a lot of people to criticize it. I mean people say, well, a physical theory, a scientific theory should be testable, which string theory isn't right now. At least it's not directly testable, because we can't see the. Strings but there is hope in testing string theory. And the hope comes from the LHC which you mentioned before.

So the LHC, which stands for Large Hadron Collider-- don't worry about what Hadron means-- will collide protons with each other at enormous speeds, with higher energies than has ever been done before. And so we'll finally have very, very energetic particles, very, very high energies to observe that have never been observed before.

And there's hope that we'll discover some new physics, and perhaps, even test string theory.

So string theory, let's see. I'll erase this guy.

String theory is called a supersymmetric theory, because it has the symmetry called supersymmetry. There are two kinds of particles. fermions and bosons. Every particle in nature can be classified as being a fermion or a boson. And it turns out that the distinguishing feature is something called spin.

So these are half, I'll just-- how do I want to say it? I'll just a say half spin. I'll have to leave you in confusion for the next 30 seconds, sorry. Half-integer spin. Integer spin.

So particles have many properties. Particles have the property of a mass. All particles have some mass. They all have some charge, some electric charge. And they all have something called the spin.

You know I can spin around and have a certain spin. The spin the particles have is an intrinsic kind of spin. The particles aren't actually spinning around on some kind of an axis. But they still have this fundamental, intrinsic angular momentum, it's called, which it's just impossible to understand on a classical, everyday level. Classical just refers to pre-quantum physics.

So it's a kind of intrinsic spin. Spin is a kind of intrinsic. Kind of intrinsic spin that all particles have. And it turns out that this spin could either be a half-integer, like 1/2, or 3/2, or 5/2, or it could be an integer like zero, one, two, three. And all particles fall into one of two categories, fermions and bosons.

Now a supersymmetric theory, a supersymmetric physical theory says that for every fermion, there's a boson. Which is to say that there is, for every given fermion, there is a boson that has every single property that the fermion has except for the spin, same mass, same electric charge, et cetera. But the spin is the opposite.

So instead of half-integer, it's integer. Instead of 1/2, maybe it's zero. So that's what a supersymmetric theory is like. It just called supersymmetry. String theory is an example of a supersymmetric theory. And so string theory predicts the existence of supersymmetric partners.

To date we haven't observed supersymmetric partners, but string theory says they should exist. Now at the LHC we'll finally have the opportunity to measure, perhaps, we will have the opportunity to see some supersymmetric partners. And therefore, we'll finally have a way of testing string theory, at least indirectly.

So if the LHC see supersymmetry, then that would be good news for string theory. If it doesn't see supersymmetry, then that wouldn't be so good news for string theory. And then the string theorists would have to work a little harder. OK, any questions about string theory?

OK, how string theory isn't the only theory of quantum gravity that people are working on. I mean it's certainly the most popular. Maybe it's the most promising. I don't know. That's not for me to say. But there are other theories that people are working on that I'll just briefly mention today. So probably the biggest competitor of the string theory is called loop quantum gravity.

Now to explain loop quantum gravity, I should probably finally explain what the word quantum means. [LAUGHS] I haven't used this word many times. You might be wondering what does quantum mean? Quantum just means the smallest unit of something. So, for example, matter has quanta. Matter comes in quanta. There's a quantum of matter.

If we take a piece of matter, you cut it in half, then you take the half, and you cut that in half, and then cut that half in half, and so forth. Can you do this process indefinitely? Can you do it infinitely many times?

Well you've all heard about atoms. Our modern scientific answer is that no, eventually you'll get to a quantum of matter. Eventually you get to an atom, then you can divide the atom into protons, neutrons, electrons.

It turns out that protons and neutrons can actually be divided even further into quarks. But then it ends there. So quarks are fundamental. Actually electrons are also fundamental. Photons are fundamental. These guys are all fundamental. So those are all the quanta of matter. The plural is quanta.

That's the plural. Loop quantum gravity not only is matter quantized, not only does matter come in quanta, but also spacetime is quantized. So space and time come in fundamental chunks.

So if you have a region of space, and you keep probing deeper, and deeper, and deeper, eventually you would reach a point where you just don't have smaller lengths anymore. You don't have smaller areas. You don't have smaller volumes. Eventually you would, you would reach a basic grain, a basic quantum of space.

So maybe it looks like this. Maybe this is how, something like this. This is how space is granular. Now it doesn't look like space is quantized. I mean it certainly looks like we can move continuously through space. It certainly looks that way. But according to loop quantum gravity, if you go deep down further enough, eventually, you reach a point where you just can't move in smaller steps than this fundamental quantum of space.

So the quantum of space turns out to be something around 10 to the minus 99 cubic centimeters. That's how small the quantum of space is in loop quantum gravity. The quantum of time is about 10 to the minus 43 seconds.

So not only is space quantized, time is also quantized. So time isn't analog. It's more like a digital thing. Time comes in steps, similar to the way a computer calculates things. If you run a program, it will run in discrete steps. So time is quantized, and space is quantized.

And it turns out that when you apply this program of quantizing spacetime, you can actually reconcile, it looks like you can actually reconcile quantum mechanics and general relativity. It looks like you can actually get a consistent theory of gravity by doing this. But there are a lot of problems. As with string theory, it hasn't been tested. And it also looks like the maybe loop quantum gravity is only a theory of gravity, only a quantum theory gravity.

You don't get the other forces. So there are a lot of the problems with every proposed theory of quantum gravity that people have thought of. There are other approaches that people have thought of. I made a list. Some include semi-classical gravity, twitch re-theory, Boolean approaches, and causal sets, just to mention some words that I talked about. I don't know anything about them.

But those are other approaches that people have thought of. But I guess the important point is to keep an open mind. Remember that ultimately experiments will determine the truth. The theory doesn't agree with the experiments, then it's no good.

We don't know what the theory of quantum gravity is today, but many people actually believe that we're getting pretty close. The string theorists believe we're getting close, and they think we're getting close. So it's quite possible that within own lifetime, we'll finally have the Theory of Everything. And perhaps that theory of everything will be simple enough to fit on a t-shirt. And I'll end there today.