NICHOLAS DIBELLA: Hi. Welcome to Excitatory Topics in Physics week 3. And boy do we have an excitatory set of topics for you today. I'll begin by reviewing special relativity from the past couple of weeks. Then I'll tell you a little bit about time travel, and then I'll talk to you about some general relativity. Then I'll tell you some more about time travel.

So for the past couple of weeks we saw that special relativity has some very interesting consequences and among them we found that some things are relative and something aren't. And we found a lot of things were relative that we wouldn't ordinarily expect to be relative. So I'll just start compiling a list here of things that are relative that we found. So some things are relative. The first example that we saw was speed.

Speed is relative. I'm going to just underline this. Speed is relative and that wasn't surprising at all, right? I mean we're used to seeing people walking on trains. Well, maybe not trains but we're used to seeing people walk by us and moving at relative speeds to us.

Something that was surprising that we found that was relative is simultaneity. If I observed two events happening at the same time-- event one, event two. Actually those weren't simultaneous events. But if I observed two events occurring simultaneously then that doesn't necessarily mean that somebody moving relative to me will also observe them to be occurring simultaneously. And that was very surprising.

Another thing we found that was relative was the time interval. The time interval between two events. And this is the phenomenon of time dilation, the fact that clocks moving relative to you run slow, they tick slower.

Also relative is length. If an object like this thing, the eraser, is moving very fast relative to you, then its length will get shorter. Its length will decrease. The length will contract. I think those are all the relative things that I talked about.

But there were some more things that are relative. Energy is relative. It's easy to see why kinetic energy has to be relative. If speed is relative then surely the kinetic energy is relative but also other types of energy are relative as well. But I won't go into detail about them.

Now, there are other things that are relative that don't necessarily have to be mathematical. Hi. There are other things that are relative they don't necessarily have to be mathematical. For example a person's accent. I mean to an American a British person would have an accent, right?

But to a British person a British person doesn't have an accent. To a British person an American person has an accent. To an American person an American person doesn't have an accent. So accents are relative.

So is humor. British humor doesn't make any sense to Americans. Well, in some people's opinions. Maybe mine, maybe not. OK.

Einstein actually had a very lovely quote summarizing the theory of relativity, what it means for things to be relative. And it goes like this, "When a man sits with a pretty girl for an hour it seems like a minute. But let him sit on a hot stove for a minute and it's longer than any hour. That's relativity." OK. I thought that was really funny.

AUDIENCE: Yeah. Our psych teacher has [INAUDIBLE].

NICHOLAS DIBELLA: Really? You've heard that? OK. But you probably laughed a lot when you first heard it.

AUDIENCE: Yes.

NICHOLAS DIBELLA: OK. OK. Not everything is relative. There are some things that we found not to be relative, and I'll make a list of those. Another word for not relative is invariant. I'm just introducing that word because I think it sounds really cool. So I'm going to use the word invariant.

Some things are invariant. That is not relative. The most important thing that's definitely not relative is the laws of physics. The laws of physics are the same for everybody. Well so far all we know is the laws of physics are the same for all inertial observers.

The laws of physics are the same for everybody that's moving, but not accelerating. If I drop a chalk here, it will fall down in a very particular way. And if I drop a chalk while moving in relative motion to the floor, then it will also fall-- well, it broke by accident, but it'll also fall in a way that's exactly predicted by certain laws of mechanics. That was the first postulate of special relativity that I introduced to you all.

The second postulate was that the speed of light is invariant. And that was also very surprising. It's surprising as any of these surprising relative things but it's true. It's been confirmed by a number of experiments.

There are other things that are invariant that I didn't get to talk about last time. One of them is the mass of an object. The mass of an object happens to be something that's invariant.

Another thing that's invariant is the electric charge of an object. For those of you who've never heard of this electric charge it's some number associated to an object that interacts electrically with another object. The object is said to have an electric charge. And it turns out that the electric charge is an invariant quantity.

Well, finally another very important invariant thing is love. Love is invariant. OK.

AUDIENCE: [INAUDIBLE].

NICHOLAS DIBELLA: I don't have the proof for that but if you ask your heart you'll know it's true. OK. Now special relativity predicts a lot of interesting things. It predicts relativity of showing quantities. And another thing it predicts is the possibility of time travel into the future. And I hinted at how this might be possible at the end of last class.

And I'd like to go over how it's actually possible through special relativity. So time travel to the future.

AUDIENCE: Can you come back?

NICHOLAS DIBELLA: The future-- what's that?

AUDIENCE: Can you come back?

NICHOLAS DIBELLA: Can you come--

AUDIENCE: Can you travel to the past? Like, if you can go to the future, can you go back?

NICHOLAS You mean can you travel back in time?

DIBELLA:

AUDIENCE: Yeah.

NICHOLAS DIBELLA: Well, I'll get to time travel to the past later on but special relativity actually doesn't provide any means of getting back.

AUDIENCE: And so [INAUDIBLE].

NICHOLAS DIBELLA: The future? Yes, the future. OK. And the way it works, as you can guess, is by using time dilation in some clever way. Yes, question?

AUDIENCE: [INAUDIBLE].

NICHOLAS DIBELLA: Oh I'm going explain how it works, OK? I'm going to explain how it works because we're limited on time. OK. With time travel in the future using special relativity all that you have to do, all that you have to do is find a spaceship on Earth, any old spaceship, get on it, travel at 99.9995% the speed of light, go about 500 light years away, then come back. And whereas 1,000 years have passed for Earth people only 10 years has passed for you. Simple as that.

AUDIENCE: [INAUDIBLE].

NICHOLAS DIBELLA: That sound simple? OK. And that works. OK. That works because of this. Suppose I'm sitting on the earth, OK, I'm sitting on the earth-- well, actually suppose you're sitting on the earth because I want to be the one in the spaceship. So as you're sitting on the earth and you observe me traveling very far, very fast away, then you observe me coming back, OK?

According to time dilation moving clocks run slow. They run slow. And therefore, if say 1,000 years passes by for you if you happen to live that long and you have the patience to do these calculations, whatever, if 1,000 years passes by for you, then less than 1,000 years will pass by for me. Now the numbers that I gave you just before are the numbers that you would get if you use the time dilation formula that I gave you last class.

So let me write it down. 99.995% the speed of light-- of the speed. We travel at this times the speed of light and 1,000 years passes by for Earth and only 10 years passed by for me. So in effect I've traveled into the future. 10 years have passed by for me and 1,000 years have passed by for you. Question?

AUDIENCE: Why don't you just go at the speed of light? Why do you have to go 99%?

NICHOLAS DIBELLA: Oh, you can't actually reach the speed of light. There are a lot of reasons you can't get to the speed of light, but one practical reason is that the closer you get to the speed of light the more energy it takes to accelerate. So from an energy point of view, to actually reached the speed of light you have to give yourself an infinite amount of energy. And where are you going to get that? I don't know. Question?

AUDIENCE: But we said moving clocks run slow. So if somehow you're able to watch, like, a rocket ship going 99.9 the speed of light, what would you see?

NICHOLAS DIBELLA: OK. The question is if I actually watched a rocket ship traveling at this really fast speed what would I see? OK. This is actually a difficulty I didn't want to get to but I'm glad you brought it up. Seeing actually isn't the same as observing. Because when you see an object you actually have to wait for the time it takes for light to travel from the object to reach you.

And so what I'm actually seeing is the past. I'm actually seeing the past. I'm seeing approximately nanoseconds in the past because it takes time for light to travel from you to me. So well, OK, so I said that traveling objects, objects in motion will get shorter, right? I said they'll get shorter.

Well, whether you actually see them to get shorter actually depends on how it's moving relative to you. So it could actually happen that you'll see an object get larger. You actually see an object get larger if it's moving at a high speed. But when you make measurements you have to take into account these corrections that involve light traveling from you to me.

And this is similar to the association you make between thunder and lightning. You see a bolt of lightning and then you hear it but you know that the sound was produced right when the lightning struck. But since it takes time for sound to travel from the lightning to you, you as a smart observer will take that into account and then say that the sound was simultaneous with the strike of lightning or at least approximately simultaneous. More nearly simultaneous than what you actually hear. OK?

OK. So 1,000 years passed by for you, 10 years passed by for me. So I'm the time traveler. Another question?

AUDIENCE: How fast is a spaceship?

NICHOLAS Oh, OK. Yeah. You actually asked that question last time and I wrote down the answer. The

DIBELLA: question is, what's the fastest speed that a human rocket has gone up to, a rocket with humans inside has gone up to? And I'll write it here. Let's see.

OK. The fastest speed traveled by humans. It was achieved by Apollo 11 before re-entry. And it was 24,759 miles per hour, which is approximately 0.0037% the speed of light. But you want to know how fast we got electrons? The fastest speed we got any particle to get-- let's see fastest speed we got any particle, I'll just write, 99.999946% the speed of light.

AUDIENCE: Wow. We're so close.

NICHOLAS DIBELLA: Yeah. We're really close. I mean, hey, this could have been 0.0000037. But if we're able to get electrons this fast, then in principle we should be able to get humans that fast. Another question?

AUDIENCE: So in theory we could put particles that could go into the future and have them come back?

NICHOLAS DIBELLA: OK. You can make particles experience time dilation but particles don't have brains. They don't have brains so who cares? OK. We do care for experimental reasons but I mean we want to know what it's like, right?

We want to know what the future is like. Yeah. OK. But if we can get particles this fast, we should be able to get us this fast in principle. We just need the right technology.

AUDIENCE: Wouldn't we fall apart if we went that fast?

NICHOLAS DIBELLA: OK. The question is, wouldn't we fall apart if we went that fast? Well we'd crush, we'd break, we'd twist, we'd get destroyed if we tried to accelerate quickly to that speed. But if we accelerate slowly to that speed, then there's not a problem, and actually I have numbers here. If you accelerate--

AUDIENCE: [INAUDIBLE].

NICHOLAS DIBELLA: I'm glad you asked that. You guys are asking questions that I had planned to talk about. That's good. OK. If you accelerated at 1 g which is the acceleration due to gravity at the surface of the Earth. If I just dropped the chalk, then it accelerates at 1 g. And 1 g is an acceleration that we're used to.

So we'd like to travel in a rocket going that fast because that's comfortable. We're used to that sort of acceleration. We're used to that kind of acceleration. That would be a comfortable acceleration. It turns out that if we accelerated at 1 g, then we'd reach-- I'll write these numbers down for you guys that are interested in all this stuff. If you accelerate-- 1 g is the acceleration due to gravity --accelerate at 1 g-- oh, we don't have all the numbers.

OK, anyway if we accelerate at 1 g reaching 99.9992% the speed of light-- I'll just write c, then-- OK, I don't have all the numbers down. But I think it's something like you'd experience-- I forgot, but you'd experience I think it's something like six years instead of-- if you traveled very far away, traveled very far away accelerating at 1 g until you reached 99.9992% the speed of light and then turned around and returned to Earth, 1,000 years would pass by for Earth and then something that's approximately 10 years would pass by for you.

But this is a more realistic situation. So it's important to know how much time actually passes by for you. And it's actually a more difficult calculation to do because it involves accelerations. Yes? Question?

AUDIENCE: How long would it take for you to accelerate to that 99.9%?

NICHOLAS DIBELLA: Oh, yeah, I said it's a harder calculation to do. I forgot what the answer is. Question?

AUDIENCE: Yeah. What kind of particles would accelerate to that percentage?

NICHOLAS DIBELLA: Oh, it's-- I forgot. It might have been electrons. It might have been muons or positrons.

AUDIENCE: I know electrons have zero mass--

NICHOLAS DIBELLA: No, no, no, no, no. Electrons don't have zero mass. Electrons have a mass of approximately 9.1 times 10 to the negative 31 kilograms.

[LAUGHTER]

Question?

AUDIENCE: Going back to the question [INAUDIBLE].

NICHOLAS DIBELLA: Are you going to answer something about the twin paradox?

AUDIENCE: Yeah.

NICHOLAS DIBELLA: Oh, let's talk about that after class. OK. Question?

AUDIENCE: 1 g equals how many--

NICHOLAS DIBELLA: Oh, OK, 1 g no it's not miles. 1 g isn't a unit of speed. 1 g is a unit of acceleration. And acceleration is measured in well, I feel like, miles and hours than it's measured in one-- well, it's measured in miles per hours squared or in units that physicists use often. It would be 9.8 meters per second squared.

AUDIENCE: Per seconds squared.

NICHOLAS DIBELLA: Yeah. That's the units for g, but it's just enough to know that 1 g is what we're used to. It's the acceleration that we're used to when we're just standing here. You have a question? Oh, OK. Oh, you're saying go on. OK. I'm going to.

OK. Now how can we actually do this and how can we actually do this in practice? What kind of ship would we produce? What kind of fuel would we use? Why did I do that? OK. How do we actually do this?

Here are the steps. I'm going to write down some steps for how you can do this if you've got the right connections. Step number one. Get a spaceship. Any old spaceship will do. Actually let me just write down the materials you need first, OK? Spaceship, very, very powerful lasers. I'll get to why in a minute. You need some very, very powerful lasers. I'll tell you why in a minute. Very powerful lasers, some very large mirrors. I'll tell you why. Not because you're a narcissist and you get bored on these trips and you just like looking at yourself.

AUDIENCE: You want to have food, water.

NICHOLAS DIBELLA: Food and water?

AUDIENCE: Who needs food and water?

NICHOLAS DIBELLA: Oh, you guys have that disease too where you need food and water? Funny. Some very large mirrors and some matter-anti-matter fuel. OK, guys. Careful. OK. Now before I tell you how to actually do this, let me tell you why you need this stuff, OK?

You need lasers and the mirrors-- the lasers and the mirrors go together. But you need them because of this very useful effect called radiation pressure. It turns out that when you shine lights at an object, the light actually pushes on it. It actually pushes on it. It exerts a force on it.

It exerts a pressure. It's what we call radiation pressure. And it turns out that if the object you're shining a light at is a reflective object, like a mirror, then you can maximize the force that you exert on the object with the light. So if we've got some very powerful lasers stationed at some places in the solar system and we've got some very large mirrors on our spaceship and we shine those lasers at the spaceship mirrors, then the lasers would actually be powerful enough to push the ship. It would be powerful enough to propel it. And this type of propelling in space is called using a LightSail.

In the ocean sailors use wind sails. They use wind. Well in space you use LightSails. Oh, by the way, in everyday life you don't notice light pushing down on you.

Like it's not pushing me down because-- it's not pushing me down because it's simply not powerful enough. It's not intense enough. The light would have to be enormously intense for you to even notice it. Yeah, I don't have any numbers on me.

AUDIENCE: Like the sun?

NICHOLAS DIBELLA: What's that?

AUDIENCE: Like the sun [INAUDIBLE]?

NICHOLAS DIBELLA: Like the sun? No, no. I mean if I go outside, I'm not immediately pushed down to the floor. No.

AUDIENCE: What if you're really close?

NICHOLAS DIBELLA: Oh, if you're really close to the sun, then yes, sure. Sure you'll be pushed by the sun, and you'll be hurt. OK. So this is how we're going to start the ship, the space ship going off. Now eventually you're going to have to turn around, right, to come back. Now how are you going to slow yourself down?

AUDIENCE: Turn off the lasers.

NICHOLAS DIBELLA: Well, if you turn off the lasers, you're still going really fast. You would just stay at that very fast speed. So you have to have some way of decelerating. And that's what the matter-anti-matter fuel is for. OK?

Now you've all heard of matter, what's anti-matter? Well, so you're all familiar with particles like protons, neutrons, electrons. Well it turns out that there exists particles in nature, which you can find and which you can make. There exists particles called anti-particles. And so--

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: I'll explain. I'll explain. I'll explain. There exists particles called anti-particles. There's an anti-proton. There's an anti-neutron. There's an anti-electron.

Now whenever a particle meets with its anti-particle, the two will annihilate each other and produce pure energy. Something like this will happen. I'll write it down here. So you have a particle right here. I'm not supposed to write on this board but I will.

So a particle here and you have another particle here. I'll just write it. They're traveling towards each other. That's too big. They're traveling towards each other.

This is the anti-particle. And this is before. I'm going to show you an after. OK. After the particle and the anti-particle won't be either anymore but instead there will be photons.

One could go this way and one could go this way. These are photons. I might have used a term earlier but a photon is just a particle of light. Light happens to come in chunks, and these chunks, these particles are called photons. OK?

Now whenever a photon hits an object, the photon will exert a pressure on it. It's the same effect. Radiation pressure applies-- it applies to light and photons are bits of light. OK. So now this deceleration problem. How are we going to decelerate?

Well initially we're traveling in such a way that our mirrors are facing-- they're facing this laser. Well if we turn the ship around and we look at our matter-anti-matter fuel and we let some of the particles annihilate the anti-particles, if we let that happen, then photons will be produced. And we can let those photons hit the mirror and thereby push the ship in the direction opposite that it was traveling initially so that effectively decelerates. It slows down the ship. And you can let this happen enough times that you eventually reach rests.

And then you have to get back. So you're too far away from the lasers and the solar system. So you turn the ship around again. No, no, no you have it the right way. You have it the right way.

You let some particles annihilate with some more anti-particles, produce more energy, then you do it enough so that the ship is moving at a fast speed again. And then you're going to have to decelerate again. And after you decelerate again, you're close enough to the lasers in the solar system to help you decelerate. And then eventually you get back. And that's all there is to it. Yes?

AUDIENCE: [INAUDIBLE]?

NICHOLAS DIBELLA: If you're smart, you'd never run out of matter-anti-matter fuel. You just put enough, right? Plan beforehand before you time travel.

AUDIENCE: What about [INAUDIBLE]?

NICHOLAS DIBELLA: Maybe you'll have to bring food. Question?

AUDIENCE: [INAUDIBLE]?

NICHOLAS DIBELLA: I can't hear you.

AUDIENCE: [INAUDIBLE]?

AUDIENCE: Repeat the question.

NICHOLAS DIBELLA: I can't hear you. Can you repeat the question.

AUDIENCE: If it has enough energy to stop [INAUDIBLE] enough energy to accelerate?

NICHOLAS DIBELLA: Oh, yeah. Once you stop you can accelerate again. Yeah, sure.

AUDIENCE: But at the same speed? Why didn't you just do that in the first place?

NICHOLAS Do you mean why didn't I use the lasers to decelerate us?

DIBELLA:

AUDIENCE: No. Why don't you use the anti-matter?

NICHOLAS DIBELLA: Oh, I could've used that first. But since we're in the solar system, what the heck. Question?

AUDIENCE: How is anti-matter created?

NICHOLAS DIBELLA: How is it created? Well it's created in a lot of different radioactive decays of particles. You might have heard of the positron. The positron is the anti-particle of the electron. And they're [INAUDIBLE] but they exist. They exist. Question?

AUDIENCE: Wouldn't that cost a lot?

NICHOLAS DIBELLA: OK. Wouldn't it cost a lot? Are we going to have enough fuel? These are questions that you have to prepare for as an aeronautical engineer. OK. Sure. And in today's world, this is completely impossible because first of all, we don't have lasers that are nearly powerful enough to exert enough pressure.

And second of all, we don't have a good way of making anti-matter. Right now we're only able to make anti-matter at a rate of about one atom at a time. And we're definitely going to need a lot more than 32 atoms to do this. Question?

AUDIENCE: How do you contain anti-matter if it just annihilates itself?

NICHOLAS DIBELLA: How are you going to-- OK. You separate them. You hold them in separate containers, the matter-anti-matter. Make sure that they don't--

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: OK. You have to have smart ways of storing this stuff. These are details. These are just little details but I'm trying to emphasize the main points. Question?

AUDIENCE: How do scientists today contain anti-matter?

NICHOLAS DIBELLA: How did they contain it? I'm not exactly sure of all these little details. But of course these are details that have to be worked out.

Anyway this is how you might conceivably reach this speed and conceivably travel into the future. Special relativity allows it. Time travel to the future is certainly possible.

AUDIENCE: Is everybody going to get back?

NICHOLAS DIBELLA: OK. There's a question of can we get back. Well I'll talk about time travel to the past in a little bit. Right now I'm still in the future, OK? I've got goals.

You know I'm thinking about the future. I'm not thinking about things that happened. OK. Well whatever.

AUDIENCE: [INAUDIBLE].

NICHOLAS DIBELLA: I'll talk about the past in a little bit, OK? OK. Now somebody was wondering about the speed that astronauts have reached, the fastest speed they've reached. Well even though it's a really, really small fraction of the speed of light, they have experienced noticeable time dilation. And they have traveled into the future more than us. I mean they've experienced less time than we've experienced.

And I looked this up. The record for an astronaut traveling into the future, the record-- the amount of time that they've gained on us-- the record amount of time that an astronaut has gained on us is 1/50 of a second. And that's 0.02 seconds. And that's a very large amount of time, right? You have a question?

Oh yeah. Yeah. OK. So there is time travel to the future for you. Time travel to the past. Is time travel to the past possible? Nobody disagrees about this. There's nothing controversial.

OK. There are engineering problems with this. There are engineering problems with this but there's certainly nothing scientifically controversial about time traveling into the future. There's nothing controversial.

However time travel into the past is more controversial. And I'll explain why. Now as far as I know, there are no ways that special relativity allows for time travel to the past. The only hopes of traveling to the past-- I don't have to say time traveling to the past, I could just say traveling to the past, right? The only hopes of traveling to the past are provided by general relativity.

So before I can tell you what these methods are, I have to tell you a little bit about general relativity. As I said, special relativity deals only with observers who are inertial, only observers who aren't accelerating. It doesn't say anything about observers that are accelerating. And so you might ask, well, can we say anything about accelerating observers? I mean they're people too, right?

OK. Well, Einstein felt the answer is yes. Yes, well certainly if we're accelerating, then things happen, right? Things in universe happen. But the question is, can we understand those things that are happening? Can we understand the laws that govern the things that we measure?

And it turns out that discovering the laws of general relativity is really hard. It's really hard to do. And it took Einstein about eight years to do it, and he was Einstein. It took him eight years to do it. So in 1905 Einstein published a paper in which he basically gave you everything about special relativity in one paper, beautiful paper.

In 1905, you got special relativity, which I'll abbreviate with SR. And after that he started thinking about accelerated motions and accelerated observers. He felt that the laws of physics should be the same for non-inertial observers. He felt it should be the same. But how might they be the same?

Well, in 1907-- they're not really important, but since I'm writing them down, it wasn't until 1915-- that's 1915, 1916 that Einstein finally got down all the laws of general relativity. But it was in 1907 that Einstein experienced what he called the happiest moments of his life. Yes, aw. The happiest moment of his life. And it was a recognition that gravity and acceleration are the same thing. Isn't that shocking or have you guys heard that?

Yeah, it's completely shocking. It's completely shocking the first time you hear it. And this realization is called the equivalence principle. And for those of you who don't-- it's not obvious at all why that's true but I'll explain in a minute why it's true. Well this is called the equivalence principle.

Gravity and acceleration are the same. But why? But why on earth would this be true? I mean, when you think about it, why on earth should it be true? Well, consider the following.

I'll give you two different situations to think about. And you'll see how this might be true. OK. First, say that you're on Earth, you're on some object that has gravity, that's exerting a gravitational influence on you. And suppose also that that object that you're standing on is not accelerating. The Earth actually is accelerating because it's revolving around the sun and it's also rotating 24 hour period but it's not doing that stuff very fast.

So the Earth is approximately inertial in the language that I used before. The Earth is a pretty good inertial place. Suppose that we're on a place where there is gravity but no acceleration. And suppose I simply drop something. I drop something.

It goes down, right? It just goes down. So that eraser is approximately a sphere so I'll draw it like this. And something goes down. This is what you see.

This is supposed to be an arrow. Physicists like to make approximations. Spheres are easy to use. Rectangular solids are harder to use. A ball or an eraser would simply move downwards like this. OK.

Consider another situation now. So you're on a rocket ship. You might notice that today I'm using a lot of rocket ship analogies and not a whole lot of trains. Trains are so yesterday, right? OK.

Well let's say that there's a ball inside of a rocket ship. And the rocket ship is accelerating but the gravity due to the rocket is negligible. So it's very small. It's not even worth considering. So let's say now that we have an accelerated place, accelerated but no gravity.

And I'll draw a rocket ship for you guys. Like I said, this is a rocket ship. It's a rocket ship.

This is a rocket ship and it's accelerating upwards. So its speed is changing, it's going upwards faster and faster. And suppose there's a ball here that simply gets dropped.

AUDIENCE: It won't go anywhere.

NICHOLAS DIBELLA: Actually it does go somewhere. But what would you see? What would you see if you're inside of this rocket ship? What would you see the ball do?

Well, you'd see the ball go downwards like this because eventually the floor reaches the ball and they meet eventually. And that's what you'd see. Or if I just forgot about the rocket ship, it would look like this. That almost looks like a person now. But it would look like this.

Now, notice that what you see in these two cases looks the same, right? A ball moves downwards at a certain rate. A ball moves downward at a certain rate and it looks the same. Now Einstein's bold move was to say, well, if it looked the same, then I'm going to postulate that they actually are the same.

I'm going a postulate that gravity and accelerated motion are actually the same thing. And that's what the equivalence principle is. Take a short break.

OK. Now this equivalence principle, first of all, it's shocking. Gravity and acceleration being the same, wouldn't expect it at all. But it actually has profound implications on the nature of space and time. It implies that spacetime has to be current.

Now what on earth does that mean? I'll write it down first. It implies that mass curves spacetime. OK. Simple sentence. Three words period. Three words.

Do you know what mass is? What does curve mean? What does spacetime mean? Well, spacetime is just the entity of space and time. And you could think of them as a unified whole.

I didn't actually get to telling you how they're actually unified but there's a very nice way in which they're unified, space and time. And we call this collective object spacetime. There's actually a very precise mathematical meaning to spacetime. And I don't know if any of you have studied differential geometry but-- I haven't, but spacetime is actually, in general relativity, a pseudo-Riemannian manifold. A pseudo-Riemannian manifold, that's just a word to impress your friends with. OK. OK.

Now what does it mean for spacetime to be curved? Well before I tell you what it's like for it to be curved, let me tell you what's like for it not to be curved, for it to be flat. Flat spacetime is simply the spacetime of special relativity. All of the equations we've got relating length and time intervals, all those equations are characteristically called flat spacetime.

Now the more you curve spacetime the more space and time will deviate from what they are like in special relativity, the more they will deviate from those formulas that I wrote down. Now to curve spacetime you simply need mass. The more mass you have at a certain place and a certain time, the more you'll curve spacetime.

And there are very interesting effects that result from the curvature of spacetime. One of them is called gravitational time dilation. Last class I talked about time dilation that results from simply the relative motion between objects. But general relativity predicts another type of time dilation which is due to gravity or acceleration. But both of them really because they are the same thing.

It predicts that time-- let's see, how do I want to phrase this? The greater the gravity the slower the time passes. I'll write that down. OK. Are you going to ask why this is true?

AUDIENCE: No. So--

NICHOLAS DIBELLA: Question?

AUDIENCE: --does that mean like time--

NICHOLAS DIBELLA: I'm going to describe it. I'm going to talk about it. I'm not going to write down a sentence and leave. OK.

So it means that the closer you are to a massive object, the slower time will pass for you. So if I'm very close to the center of the Earth-- well, I'm not very close to the center of the Earth right now, but I'm closer to the surface of the Earth than I could be. So right now I'm a certain distance from the center of the Earth and I experience a certain amount of gravity. If I were to travel 100 miles upwards, then gravity would be much weaker. You all know that because you're simply farther away from the source of gravity.

Well, according to general relativity, time will pass by slower for the person closer to the center of the gravity. Time will pass by slower for clocks in greater gravity. And this is something I was thinking about. I don't know about any of you guys, but I used to share a bunk bed with my brother for several years. And I slept on the top, he slept on the bottom.

So he actually aged less than me during those years and I'm the older brother too. So I should have been the one aging less. That's unfair. And I didn't realize that until I learned about gravitational time dilation. Then I kicked him out of the room.

Well, something like that happened. OK. And this happens because of this very powerful principle of general relativity, which is that mass curves space and time. Time intervals will be different from what you would expect in a special relativistic universe, and spatial intervals will be different. And that's simply what we mean by curved spacetime.

OK. You can use the gravitational time dilation as another means for traveling into the future. I'll get to the past soon, don't worry. But you can use gravitational time dilation as another means for traveling into the future. All you need to do is find a mass of objects, stay near it for a while-- actually this isn't very massive because the earth is much more massive than this wall. But find a massive object, stay near it for a long time, and some amount of time will have passed by for you and a much longer amount of time will have passed by for people far away from you.

So for example 10 years passed by for you whereas 100 years will pass by somebody else. And I can give you a fun formula to play with but I might be running low on time. OK. Yeah. I'll give you a cool formula to play with at the end of the class if there's time, but there might not be time. If only we could have a machine for dilating time. If only we could have a time machine. Question?

AUDIENCE: So if you live right to Mt. Everest--

NICHOLAS DIBELLA: I'm sorry. Say that again.

AUDIENCE: So if you live like right next to Mt. Everest, you'll have a little more--

NICHOLAS DIBELLA: OK. If you live next to Mt. Everest, will time go slower for you? You mean like if you lived next to the base of it which is very massive is what you're saying?

AUDIENCE: Yeah.

NICHOLAS DIBELLA: OK. Well, yeah sure. Time will go by slower for you but the Earth is so much more massive than Mt. Everest. I mean as big as Mount Everest is, the Earth is much bigger. So, yeah time would go by slower for you but not to a very noticeable amount.

I need to go next to something that's very massive, something enormously massive, something as massive as a black hole. If we could find one or if we could make one. OK. I was getting to dramatic. Is that readable? OK. It says black hole.

I'm sure you've all heard of black holes. And maybe a lot of you know what a black hole is but maybe not in the context of general relativity. General relativity predicts the existence of objects called black holes but so does Newtonian gravity. Newtonian gravity also predicts the existence of black holes. Now what is a black hole?

Well it's simply a region of space where there is so much mass that if an object gets too close to it, then there is a point where if the object passes it, it simply can't return. There's a point of no return. And that point of no return is called the event horizon if any of you have heard that word before. It's called the event horizon.

In language of Newton massive objects attract each other because there's a gravitational force. And the force is a concept that's used a lot in Newtonian physics. It's a very useful concept but Einstein actually throws that concept away. In general relativity there's no need for a notion of force. Everything's curvature.

And here's what I mean. OK. I'll talk more about black holes in a minute. Let me just explain this thing about curvature and how objects move in general relativity. OK. So in the Newtonian way of thinking if I drop an object, it will fall down because there is a gravitational attraction between the object and the center of the Earth. That's the direction it's moving.

So it falls downwards. That's the direction of the force. Well, general relativity has a different way of describing motion. It has a way of describing motion by what's called geodesics. And forget about that word for right now. Forget about that word for right now. OK.

OK. Here's how general relativity describes motion. So I have an object here, right? And I'm wondering, how is it going to move? You all know how it's going to move but suppose you didn't know how it's going to move. You can conceive of lots of different ways.

You can conceive of lots of different ways that a given object can move. It might go upwards. Don't laugh. You know the answer but what if you didn't know the answer. It can go upwards.

It can go downwards. Maybe? It can go sideways. It can go some weird curvy path. It could go this way.

It could go this way, go this way, go this way, go this way, go this way, go this way, go this way, go this way, go this way, go this way, go this way, go this way, go this way, go this way and then end up right there and stay there. That's conceivable, right? It's not logically, not philosophically impossible to happen. You can think of that as a possibility.

Well, according to general relativity, first of all mass tells spacetime how to curve. So there's a given amount of mass here and there's a given distribution of mass, and it tells spacetime how to curve. But how does the object move? Well, spacetime tells the object how to move.

So mass grips spacetime, mass grips spacetime and tells it how to curve. And spacetime grips mass and tells it how to move. That's the key idea of how general relativity works.

Now how exactly does spacetime tell mass how to move? Well, let's think about it. Well, let me explain it. So there's an object here. It can go this way, it can go a little bit this way, go a little bit this way, a little bit this way, a little bit this way.

But for each infinitesimal step that it makes, the laws of general relativity say that the object will travel in a path such that the time experienced by the object will be maximized or minimized. One of the two, but not both. When you saw for the equations of motion, only one of the two will actually be a physical answer. So because spacetime is curved in a very specific way due to this mass, the object will have aged in different ways, depending on which way the object could move.

Well, it turns out that the object will travel downwards as you all know because that's the path which gives rise to maximal aging of the objects. And this is simply a fact that comes out of general relativity, simply what happens. And objects will move to extremize their time, maximize or minimize. Only one of the two will actually happen. OK.

Now to get back to black holes. OK. Now, as I said, in the language of Newton we would say that a black hole is something that's so massive that there's a point of no return. Nothing can escape, not even light. In the language of general relativity, a black hole is a region of space where the spacetime is curved so much that if an object reaches this point of no return, the spacetime is simply too curved for the object to get out of it. It's simply too curved to get back.

And my shirt actually illustrates this. OK. So this is supposed to be a representation of a black hole. Forget about this formula next to it. But this is supposed to be a representation of a black hole. As you get closer to the center of a black hole, spacetime will get more curved.

The closer you get, the more curved spacetime becomes. And there's a point in the center where mathematically space and time actually become infinitely curved. And one could say, well, spacetime ceases to exist at the center of a black hole. And that's called the singularity of a black hole. And the spacetime approaches infinite curvature at the singularity because actually it's just a point and there's mass contained in that point.

So there's actually infinite density at the singularity of a black hole. And this has mystified physicists for a very long time because we're not sure what to make of it. Whenever we see infinities crop up in physics, we think well maybe there's something wrong with the theory. But I'll get to this point eventually.

Most physicists suspect that there actually aren't singularities at the center of a black hole. They suspect that space and time still exists there but quantum effects sort of smooth out the space and the time and give rise to some finite amount of curvature at the center. Question?

AUDIENCE: On average, how big is an event horizon?

NICHOLAS DIBELLA: Excuse me?

AUDIENCE: On average, how big is an event horizon?

NICHOLAS DIBELLA: On average, how big is an event horizon? You mean how far away from the center of a black hole might it be on the average?

AUDIENCE: How big.

NICHOLAS DIBELLA: Oh, how large? Well, you're going to have black holes of various sizes. Theoretically you could have a black hole the size of a centimeter. Actually, since you brought it up, I'll talk about this formula on my shirt. OK.

There's a formula that says how large a region of space has to be such that a given amount of mass in that space is actually enough mass to make a black hole. So if I took a lot of mass and compressed it so that it had a really high density, then it would reach the size necessary to make a black hole. At a certain radius from the center of this mass, suppose it's spherical, at the center of this mass called the Schwarzschild radius.

And there's a formula for the Schwarzschild radius. Rs equals 2MG over C squared. M is the mass of the object, C is the speed of light, and G is like constant. Well, if you're curious about it I'll explain more after class but we're kind of running out of time.

AUDIENCE: Is that the same G Newton had?

NICHOLAS DIBELLA: Yeah. It's the same G that appears in Newtonian gravity. And you actually get the right answer if you use Newtonian gravity. You get the same answer in general relativity and Newtonian gravity. And it's interesting that that happens. OK.

Well, just a final couple of notes on black holes. Do they exist? Well I've never seen one because they're black. Light can't get out of them. We can't actually see them but there is a lot of evidence for the existence of black holes.

One simple piece of evidence is that we see a lot of objects in the universe moving in certain ways but they're moving in certain ways that indicates there should be something here. But if we don't see something there, then well we can guess maybe it's a black hole. That's one simple way of possibly indirectly detecting a black hole. But there are a lot of other ways too.

AUDIENCE: [INAUDIBLE]. Why don't all the black holes come together and just stay there?

NICHOLAS DIBELLA: Why don't all the black holes simply meet up with each other, you're asking?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Because they attract each other?

AUDIENCE: Yes. If everything attracts everything else, why is it to be [INAUDIBLE]?

NICHOLAS DIBELLA: OK. The question is if everything attracts everything else, then why isn't everything moving towards each other? And that's because well, because in the early universe the universe underwent massive expansion. So that's-- this is a cosmology topic, which will be talked about in a few weeks. But the fact is that they were initially moving very fast away from each other so that they don't meet up with each other. OK.

The universe is not static. If the universe were static, you would eventually expect for everything-- is that right? You can eventually expect for everything to meet up with each other? Anyway, this will be talked about in a few weeks.

General relativity also predicts the existence of strange objects called wormholes. And these are really strange. I can't describe them in very much detail but they work very simply. A wormhole has two mouths, and it has a tunnel connecting the two mouths.

Now a wormhole is a path between two regions in space. But it's more than just a path between two regions of space. It's a shortcut between those two regions. If you find the mouth of a wormhole, you go inside the mouth, you travel through the throat of the wormhole, and then come out. You exit through the other mouth.

Then you'll have taken a shortcut through space to get from one region in space to another time very quickly. You could beat out white in a race. Question?

AUDIENCE: If you have a wrinkle in spacetime, [INAUDIBLE]? If you were thinking of spacetime as a flat sheet, would a wormhole be--

NICHOLAS DIBELLA: OK. She's asking about a common way that people use to represent wormholes. I know what you're thinking about. OK. We can represent a wormhole quite simply. I'll draw the representation first and then I'll explain it. OK.

OK. Suppose the universe is two dimensional. There are two dimensions of space. So suppose it's a flat sheet. So let's suppose that this is the universe. This is a piece of the universe.

And this is also a piece of the universe. And this is a wormhole. A wormhole connects two pieces of the universe in a path that can conceivably be a much shorter length than the path it would actually take to travel across the universe to get to the other mouth of the wormhole. Now this kind of diagram can be very confusing. Like, what is this space over here?

It's the one they call hyperspace but it actually isn't anything. It's a fictitious element in a diagram. This isn't anything. It's simply a way of representing a wormhole. But some people find it useful to think about wormholes in this stuff.

Like, what does this curve mean? Don't worry about it? It doesn't really mean anything, doesn't really mean a whole lot. OK.

Wormholes provide a method of traveling to the past. And I'll explain how it might be possible. OK. Here's what you do. I don't actually need to draw anything. I could just use that.

Well, I could just describe it to you. OK. Suppose you've somehow created a wormhole between two regions in space. We're not going to say how but suppose you did. The actual construction process is very difficult. And you might actually need a time machine to make one.

So some people are highly skeptical of the possibility of constructing a wormhole. But suppose you have constructed one. Suppose you've created something capable of connecting two regions in space such that you can get from one point to another pretty fast. Like you have a [INAUDIBLE] that's only 10 feet long for instance.

Suppose you've created a wormhole. Now the wormhole has two mouths. One mouth could be next to Earth for instance. Another mouth could be next to some galaxy. And here's how you could use the wormhole as a time machine.

You first take one of the mouths and accelerate it to a very high fraction of the speed of light relative to the Earth. OK. Relative to the Earth. OK. So you make it go really fast and very far away from the Earth. And then you make it go really fast and come back to the Earth. So according to special relativity-- and that first way of traveling through time to the future, according to special relativity then the top mouth-- let's suppose it was the top mouth that we accelerated, the top mouth-- sorry let me just bring this down, the top mouth will have aged less than the bottom mouth.

So somebody sitting on the Earth we'll say, for instance, five years have passed by for the top mouth but 10 years have passed by for the bottom mouth and also 10 years will have passed by for Earth. OK? So now, for instance, the top mouth could be at the year 2005 and the bottom mouth could be at the year 2010, let's say. OK. Suppose we started at the year 2000, and it took us five years to go back and forward, forward and back. OK. Now, so this is a very confusing point what I'm about to say. Now it turns out that if you're inside of the wormhole, then you'll always observe clocks on the two mouths to be synchronized with each other.

Synchronized just means that they show the same time. You'll observe them to always show the same time. So time connects differently depending on whether you're outside of the wormhole or whether you're inside the wormhole. If you're outside the wormhole, then the clocks at the mouth of the wormhole and the bottom wormhole do not have to be synchronized. They don't have to be synchronized.

But it's a consequence of chugging through the equations of general relativity that if you're inside the wormhole, then you'll always observe clocks at the top and the bottom to be synchronized. So if you've accelerated the top mouth of the wormhole to an appreciable fraction of the speed of light and then you brought it back, then it could be, for instance, the year 2005. I'll write this-- could be the year 2005 here and the year 2010 here. Actually this is probably far off in the future, so let's say 3010 and 3005. Go ahead.

OK. So you've done this. OK. You've done the acceleration and you've brought it back. OK. Now say you go inside the wormhole. OK. Starting from the top. It's 3005 for you, and you go inside the wormhole.

So your clock initially says 3005. Well, if you go inside the wormhole, then you have to observe the clocks at both mouths to be synchronized. You have to. I can't really explain why because you have to go through the general relativity to get at that result. I don't know of an easier way to explain how it has to be why, why it has to be true.

But you go inside the wormhole and the two clocks have to be synchronized. So if you started at the top, it's 3005 for you. Then when you exit out of the bottom, it's 3005 again. It's 3005 again. So it's now 3005 at the bottom of the wormhole for you.

And you can travel back to Earth, and well, it will be 3005 again on Earth. But you'll have traveled back in time via a wormhole by this construction, this method which is very hard to understand, very hard to prove. And I can't really give a good explanation for why it works other than very, very smart physicists, who know a lot more than I do, have worked it out and have come at this results. One second, one second. So the way I've just described, you can use wormholes as time machines. OK?

But you can't actually use a wormhole to travel farther in the past than when the wormhole was created. So if the wormhole was created in the year 3000, then you can't travel to the year 2007. And why? Well simply because you can only get to the time of the accelerated mouth of the wormhole.

And the fact that you can't create this wormhole time machine to get you to a farther past than when you created the time machine is an interesting answer to a very important question posed by Stephen Hawking. Which is that, if time travel is possible, then where are all of the time travel tourists, right? Where are they? And this provides an explanation. It's simply that no time machine has been constructed yet so none of the time travelers have been able to travel to our time. Question?

AUDIENCE: How would you make a wormhole?

NICHOLAS DIBELLA: I told you, it's really a complicated. Question?

AUDIENCE: Is it safe to go through a wormhole?

NICHOLAS DIBELLA: Oh. Is it safe to go through a wormhole? Well, it turns out that wormholes are highly unstable objects. And the moment you get inside one, a wormhole will very, very quickly form a singularity inside of it. So space and time will cease to exist for you and you'll be crushed and so forth.

But a wormhole can be stabilized if you've got some exotic matter. But any exotic matter is you get matter with effectively negative mass. It's really crazy to think about, but actually some particle physics theories predict the existence of some negative mass particles that, for example, have to be present in the early universe. And so it could be that in the early universe there were a lot of time machines present, a lot of wormholes, a lot of black holes, lots of crazy stuff.

So is time travel possible? Well, to the future, certainly. Nobody disagrees about that.

To the past, maybe. We're not so sure about that. But to the future certainly we're traveling in the future. And it's always fun to think about.