NICHOLAS DIBELLA: So this is the fifth week. I guess it's about halfway over now, the class, HSSP for the summer. Thanks. I know we looked at some-- oh, question?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Yeah, you can get it at the end of class, or at the break. OK, so we've looked at some big question so far in the past four weeks. Most of these have concerned the whole universe.

Did the universe have a beginning? Will the universe have an end? Is the universe infinite? Are there parallel universes?

Is there other intelligent life in the universe besides us? And these are some pretty big questions, I think. Today, I would like to change the subject and discuss the nature of space and time, particularly time and whether the possibility of time travel is possible. So that's what we'll talk about today.

Now, time travel is certainly something we've all thought about before, probably somebody we've all wished for at some time. I mean, how many of us would like to go back to the '60s, and see the Beatles, or something like that? Yeah, that would be great, right? Or maybe go back--

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: OK, yeah, I mean, certainly the past would be fun to see, but the future as well. Yeah, it would be cool to know what technology is like in 7,000 years from now. We've only been really engaged in modern technology just for the past 200 years or. Imagine what technology will be like in 7,000 years, or 10,000 years, or a million years.

So there are all sorts of reasons for wanting to go to the future, all sorts of reasons wanting to go to the past. Maybe I said something yesterday that I wish I didn't say. It would be nice to fix it so I'm not as distressed as I am today.

So there's all sorts of reasons for wanting time travel. And just from a scientific perspective, it's interesting to know if it's possible. Is it physically possible to travel through time?

So to really get a hold of these questions, we have to understand what time is. So what is time? Can anybody give a definition for what time is? Yeah?

AUDIENCE: Something that ticks.

NICHOLAS DIBELLA: Something that ticks. That's a really good definition, actually. That's a really good definition. Well, not something that ticks, but the thing that's responsible for the ticking.

That's probably a better definition. But, yeah, that's a pretty good definition to define in terms of things that happen. Anybody else have a definition for what time is? Yeah?

AUDIENCE: It's an infinite one way flow of events in history.

NICHOLAS DIBELLA: An infinite one way flow of events in history. OK.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Yeah, if it's a one way flow, that would imply that you can't go back. But at least it seems to flow in one direction. There seems to be an arrow in time.

Yeah, it actually turns out to be really hard to define what time is. And it's much easier to define how time operates, like in terms of how it acts on things. So if I look at a clock, I see a ticking, then I can say, well, time is acting. Time is responsible for the ticking. And that's a much easier way to define time. Yeah?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Time doesn't--

AUDIENCE: Time doesn't actually [INAUDIBLE]

We are the ones that are actually aging. So everything is happening

[INTERPOSING VOICES]

AUDIENCE: Because we can [INAUDIBLE] or change. It's us [INAUDIBLE] time itself.

NICHOLAS DIBELLA: So time doesn't flow. We flow through time. Yeah, I'll talk about time. Yeah, that's certainly one way of looking at time. Yes?

AUDIENCE: Doesn't time stop in black holes?

NICHOLAS DIBELLA: Doesn't time stop in black holes? In a sense. But it would take me about three minutes to explain that in a sense. So I'll get to this later, how gravity actually affects time.

So the theory that we have today that explains the nature of space and time is Einstein's theory of relativity. But before relativity, the way that people thought of time was the way that Newton essentially proposed the think of time.

So the way Isaac Newton thought of time was he thought of space and time as absolutes. And here's what I mean by absolute. So space is this thing that all the events of the universe happen inside of.

It's like a stage. It's a background. Space is the background in which things happen. And time is just this thing that's responsible-- it's just this thing that continually flows in space.

Things happen in time. Time is also like a background. It's always ticking everywhere. And according to Newton, space and time are completely separate things.

And they're completely independent of all the objects in the universe. So I don't affect time. You don't affect time. I don't affect space. You don't affect space.

They're these completely separate things that exist out there. We can't affect it in any kind of way. And I can ask I can ask questions like, how does my time compare to your time? Or how does my space compare to your space?

And when I say space, I'm not just referring to outer space. I'm referring to just locations. I mean, we're in space. This is one point in space. This is another point in space.

That's just what I mean by space. I am not necessarily referring to outer space. But you can ask questions.

Like suppose two events happened. Suppose lightning strikes, and then a baby cries, two things happen. You can ask, what's the duration between the two events?

So suppose I had a clock, or a stopwatch. And I just timed how long it takes before the baby cries after the lightning strikes. And maybe I'll get something like five seconds.

Then I can ask the question, well, what do you get? Suppose you were to do the same simple experiment. Suppose you took out a watch, and you also timed it. What would you get?

What would you get if you were traveling at some speed, according to me, or if you're flying, or something like that? Well, according to Newton, according to his absolute time, everybody would get the same time interval between the two events.

Also, if you measure the distance between the two events, maybe I'll measure the lightning to strike two miles away, and the baby cries right over here. What do you get? Do you get two miles?

Do you get some other number? Does it matter if you're flying? Or does it matter if you're traveling some

Well, according to Newton, space and time are absolutes. And that means that we all agree on these time intervals that we get. We all agree on these lengths that we get.

It's a very common sense idea. Why should it be any different? That would be crazy, right?

Well, it turns out that nature is crazy, because, in fact, space and time aren't absolute. So about 100 years ago or so-- what's that?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: It turns out, no. And I'm going to explain that. So at the beginning of the last century, at the beginning of the 1900s, people started noticing some things, some phenomena that happened in the world, that Newton's theory just has a hard time explaining, or else just can't explain at all.

And so Newton's theory was kind of in trouble. And people had tried to fix the theory, tried to think of ways of getting around it to make the theory work. I won't go into the details of this.

This will have to wait for maybe two weeks from today. But for now, just know that Newton's theory was in trouble. It was in trouble. It had a problem.

And finally, somebody came along, and fixed these problems, found a way to solve these problems. And that was Einstein, when he proposed his theory of special relativity. So, eventually special relativity came around.

And it fixed all these problems. It's actually a very simple theory. It's just based on two fundamental principles, two fundamental postulates we call them. A postulate means it's something that it's totally fundamental. You can't derive it.

You can't justify it. It just is. It doesn't make any sense to ask why it is. It just is.

So the first postulate of special relativity is that the laws of physics are the same for everybody. I'll explain in a minute why I have everybody in quotes. The second postulate is that the speed of light is the same for everybody.

OK, now, when I say everybody, I don't really mean everybody. I have some particular type of everybody in mind. So when I say everybody, I mean everybody that's moving at some constant velocity, or some constant speed.

So if I'm walking at two miles per hour, if my speed is not changing then I'm moving at a constant velocity. And I would be the type of everybody that special relativity refers to. I'm called an inertial observer. But that's just a word.

If I'm at rest, if I'm not moving at all to you guys, then I'm also moving at a constant speed. So I would also be a valid observer. But if I start at rest, and then start walking faster, and faster, and faster, and faster, and faster, then my speed is gradually changed.

And so I've accelerated. I would be an accelerated observer. I would be a non-inertial observer. So then special relativity wouldn't apply to me.

And you actually need general relativity, which is the extension of special relativity to take into account accelerated observers. But I'll talk about general relativity later. So the first postulate is very simple, very easy to accept. The laws of physics are the same for everybody.

I mean, that's easy to accept. Nature is fair. We all obey the same laws of physics.

So if I drop the chalk, gravity will act in a certain way. The law of gravity acts in a certain way. And it shouldn't matter whether I'm dropping the chalk, or whether you're dropping the chalk.

The same law of gravity will work for both of us, the same law. It shouldn't matter if you're standing still, or if you're moving at some constant speed. The law of gravity will be the same. And all the other laws will be the same.

That's just what the first postulate says. The second postulate is weird. The second postulate is weird.

And to demonstrate why it's weird, I need a volunteer, just a very simple experiment. It will take two minutes. You're closer, so OK.

OK, so do you know how to walk?

AUDIENCE: Probably.

NICHOLAS DIBELLA: OK, so let's start over here. We're going to walk across the room. And I'm going to ask you to walk about half my speed.

Actually, let me walk over here. I'm going to ask you to walk about half my speed. You can keep walking. What's that?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: OK, he should have been halfway across here. Let's assume that he was. Let's assume he was a competent volunteer. OK, so how fast would you say I was walking?

Pretty slow, let's say two miles per hour. And so he was walking one miles per hour. OK, that's the speed that you guys measured, right? I was walking two. He was walking one.

So according to you, relative to you, I was walking two. And he was walking one. Now, relative to you, how fast was I walking?

AUDIENCE: One.

NICHOLAS DIBELLA: One, yeah, it's just two minus one. You just subtract it. And relative to you--

AUDIENCE: But relative to me, they would be walking negative one?

NICHOLAS DIBELLA: Yeah, so relative to you, they're actually moving. They're actually moving that way, relative to you. So the whole notion of motion, that's a fun phrase to say, the whole notion of motion depends on the observer.

So it doesn't make any sense to say that somebody is moving with some speed, unless you have some kind of observer in mind. So if I'm walking two miles per hour, you have to say, I'm walking at two miles per hour relative to some observer. So relative to the people sitting in the classroom, I'm walking two miles per hour.

Relative to the classroom-- what's your name?

AUDIENCE: Fred.

NICHOLAS DIBELLA: Fred is walking at one miles per hour. But relative to Fred, I'm walking at one miles per hour. And relative to Fred, Fred's not walking at any speed. He's at rest, relative to himself. Right?

OK, thanks. So that's all that relativity is. Some people measure one thing. Other people measure something else. That's just relativity.

It's relative. It's all relative. So that's the relativity of speed.

Now, the second postulate says that-- well, let's suppose that I was light. Well, actually let's forget about Fred. Let's just talk about me.

Let's say I shine a flashlight. Light travels at some speed outside the flashlight, some speed. It turns out to be about 186,000 miles per second, very fast.

The second postulate says that I'll measure the same speed, regardless of whether I'm standing still, or whether I'm walking. Remember when we asked, what speed does Fred get when he measures my speed? We have to do some kind of subtraction.

It's very intuitive. You just you just subtract it. You just subtract, it's called the relative velocity. But according to the second postulate, you don't do the subtraction for light.

Light travels at the same speed for everybody. If you were to chase light, you would never get any closer to it. It would always travel the same speed from you. You'd always be chasing it.

You can't reach it. It's going so fast. Sorry, what?

AUDIENCE: [INAUDIBLE]. Well,

NICHOLAS DIBELLA: I mean--

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Excuse me?

AUDIENCE: [INAUDIBLE]

And you start walking [INAUDIBLE]

NICHOLAS DIBELLA: Well, I mean, in real life light actually gets absorbed by some materials. And so it actually gets stopped by some materials. Let's suppose this isn't the real world.

Let's suppose this is empty space. There's nothing to absorb the light. The light would just keep traveling. Nothing would stop it.

So if I turn on the flashlight, the light is traveling at some speed relative to me. And then if I'm walking at some speed relative to you, light is traveling at the same speed. And regardless of how fast I'm walking relative to you, or I'm driving relative to you, or I'm flying relative to you, light will always be going at that same speed. It's as though we're trying to chase it, and we just can't get it. It's just completely out of our reach. Yes?

AUDIENCE: [INAUDIBLE]

--miles per hour, and then you turn [INAUDIBLE]

NICHOLAS DIBELLA: So the question is, is that why when we're in the car and we turn on lights, light is always in front of you?

Even if the second postulate weren't true, that would still be the case, because light is traveling so fast, you're not going to catch up to it. But even if you made the car go extremely, extremely, extremely fast, then you still wouldn't catch up to the light. It actually turns out to be impossible to beat light in a race.

You can never travel faster than light. Well, strictly speaking, you can never start out at a speed less than light, less than the light speed, and then get faster than it. So some people have actually considered the possibility of particles that travel faster than light called tachyons.

But nobody has ever observed a tachyon. They're completely hypothetical. And nobody has any idea whether they exist. So we won't talk about tachyons for the rest of the class.

But they're fun to think about in sci-fi. And they're just fun to think about. OK, so these are the two postulates. The first one is quite simple. The second one is completely mysterious.

Now, it turns out that these two postulates actually have a lot of really interesting consequences. The second postulate itself, I think it's very interesting. Oh, by the way, it's also been confirmed experimentally. This isn't just something that people say.

People have tried to see if the speed of light changes, depending on how you move. And they found that it doesn't. They found a null result in these experiments. The speed of light doesn't change, regardless of how you move relative to space. That's just something in the early 20th century that people were trying to figure out, whether light propagates inside some kind of mysterious medium. Anyway, that's another thing.

So these two postulates have a number of very interesting consequences. Probably the most interesting is called time dilation. And this says that moving clocks tick slow. They tick slower than if they weren't moving.

So let's suppose it's some summer day, some summer afternoon, like today, a beautiful summer afternoon. And you have free time. And so you decide to do your favorite activity on the summer afternoon.

You go to the train track. And you like to watch the trains go by. It's very relaxing. That's what you like to do in summer afternoons.

So you go to the train track, and sit down on a bench. And you watch the trains go by. You also like to measure things with your clock.

So you bring a clock along. And you like to think about how time passes for you, and how it passes for observers sitting on the train. So let's suppose this is you sitting on-- let's suppose this is you.

No, OK, whatever, let's suppose this is you sitting on the bench. A bench is too hard to draw. So I'm not going to draw the bench. So you're sitting on the bench, which I've represented as nothing.

And a train passes by, which I'll represent with a rectangle. It's going this way. Maybe it looks like a bus. Let's suppose it's a train.

When Einstein was thinking of these thought experiments, he always used train, because back then that was the fastest kind of vehicle that people had invented. Cars, they weren't able to go as fast as trains back then.

Now we have cars. Now we have planes. Like in a modern thought experiment, this is just a thought experiment just think about we don't actually do it. In a modern thought experiment, we might use planes, or maybe spaceships, or something like that.

Let's think about trains right now, just keep it very simple. So you're sitting on your bench. And you watch the trains go by.

Then you wonder to yourself, let's suppose that some amount of time passes by for me sitting on the bench. And I look at my clock. I get something. I get some number.

What number do people on the train get? So let's say, for example, it's very relaxing. It's very relaxing to sit on these benches at the train track.

And you accidentally doze off. You fall asleep. Or maybe it was due to the heat. The heat got you.

You fell asleep, in any case. And let's say, somehow, you timed yourself to see how long you were sleeping for. And let's say you got three hours. You determined that you're sleeping for three hours.

How long do the people on the train see you sleeping for? Well, according to special relativity, it turns out that if you work out the mathematical and geometrical consequences of these two postulates. You get this time dilation effect, that moving clocks tick slower.

So if you were to look at a clock on the train, you'd see them ticking slower than your clock. So maybe your clock is ticking at this rate. You just look at it. It's going something like this.

That's too slow, sorry. Your clock is maybe ticking at this rate. It goes around 12 to 12. And maybe the clock on the train is going at this rate, relative to that one.

And so you measure three hours sitting on the bench. What does somebody on the train measure? Well, since the clock is ticking slower, as a certain amount passes by on your clock-- say it's 3:00 o'clock.

And a certain amount of time passes by your clock. Since this guy was ticking slower, since this clock was ticking slower, a smaller amount of time will have passed by. So maybe for them, only two hours has passed by. And this is exactly the--

AUDIENCE: [INAUDIBLE] are always early?

NICHOLAS DIBELLA: No, no they're not--

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: No, no, I'm saying something very precise. I'm saying that if a certain amount of time passes by for somebody stationary, then a smaller amount of time passes by for somebody that's moving.

AUDIENCE: [INAUDIBLE] very, very high speed.

NICHOLAS DIBELLA: OK, so you might wonder, we never see this happen. It seems like time is an absolute thing. It seems like everybody agrees on the same time intervals. Why don't we actually see this happen?

It turns out for these effects to become noticeable, the speeds involved have to be near the speed of light. And the speed of light is really fast. I mean, how fast does a train move? 50 miles an hour, I don't know.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Would the train fall apart if you made it move really fast? Well--

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Well, the thing that would cause it to fall apart is when you're accelerating. You have to push it in some kind of a way. Once it's going at a constant speed, it's not feeling any force. It's not feeling any push or pull.

But the part that might break it is when you're actually accelerating it. You have to actually give it a push in order to get it to go some speed. And that push might be too much for a train to withstand.

AUDIENCE: So you'd probably want a really long train to [INAUDIBLE]

NICHOLAS DIBELLA: Well, you don't want to try with a train. I mean, this is just a thought experiment. We're not actually going to do this experiment. It's just an experiment that we can think of in our minds to help us understand the ideas.

If you like, you can do the experiments in your thought lab. The thought lab is a very nice lab, in that it's free. Everybody has one. You can always do thought experiments.

But it's also a very dangerous place, because like you were saying, if you made a train go too fast, if you tried to accelerate to make it go so fast, it might explode or something. And your thought lab might need serious repairs. So the thought lab is very dangerous.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: So light is very special. Light is very special. Light always travels at the speed of light.

It doesn't have to accelerate to get there. It's just always traveling at the speed of light. It's very mysterious.

AUDIENCE: But then what if your flashlight's off?

NICHOLAS DIBELLA: If your flashlight is off, it's no longer producing light. The flashlight produces light. And then the light that's produced automatically travels at some speed. When you turn off the flashlight, light is no longer being produced.

So there's just no more light. But the light that you did produce is traveling at the speed of light until it reaches some material that it gets absorbed. But if you did this in empty space, if you did it in outer space where there's nothing, then it wouldn't get absorbed. It would just keep traveling, and traveling, and traveling at the same speed. Question?

AUDIENCE: If you shone a flashlight in space, could you see the light moving forward?

NICHOLAS DIBELLA: If I shone a flashlight in space then would I see the light moving forward? I'm not exactly sure what you mean.

AUDIENCE: If you turned it on, and the light was going, and you--

NICHOLAS DIBELLA: Oh, like maybe I've got a laser right here on the surface of the table. And it's shining right there. And I'll suppose that this whole room is outer space. Would I see something right there?

Would I see a line of light kind of like that? No I wouldn't, because the light has to reflect off a something for me to be able to see it. So if there's nothing there, it's not going to reflect off of anything. So I'm not going to see it.

AUDIENCE: How do we see stars?

NICHOLAS DIBELLA: Well, the light eventually, it hits stuff. And it reaches us. Space isn't completely empty. There's some stuff.

There's some dust that the light hits off. It hits off of some dust. So space is almost empty.

But you get about one hydrogen atom per cubic meter. It's very not dense. But there is some stuff in space.

So this time dilation effects-- moving clocks tick slow. So, as I say, it's important whenever you're going to mention any speed at all, it's important to mention the observer that you have in mind. It's always important to mention what the speed is relative to somebody.

So as I'm walking, you guys would say that I'm moving. But I would say that you're moving. I'm traveling at two miles an hour relative to you. You're traveling at two miles an hour relative to me.

And, similarly, this time dilation effect works in the same way. So this time dilation effects is also symmetrical. There's a symmetry.

If I observe your clocks ticking slow, then you'll observe my clock to be ticking slow. It's symmetrical. Yes?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: So does the discrepancy between cell phone times have anything to do with time dilation? That's your question, right? I don't really know a whole lot about how cell phones work.

But I do know this. If the cell phone uses GPS at all, if it uses these satellites, these global positioning satellites, there are actually time dilation effects that you have to take into account to get things right, to pin down this location of a place right, because you have to communicate with the satellites that the light bounces back up and forth. You have to communicate with them.

And you actually have to take into account a different type of time dilation. Gravitational time dilation ends up being important. And that's actually an effect to the general relativity. I'll get to that later today.

But I have no idea. I don't know how cell phones work. I can't really answer that question.

So a moving observer-- I'll say your clocks are moving slow. You'll say my clocks are moving slow. Time relation is reciprocal. It's symmetric.

Neither of us is wrong. I'm not wrong to say that a certain amount of time passes by, and you say another amount of time passes by. Neither of us is wrong. We just have different perspectives.

It doesn't make any sense to say, well, precisely three hours past. It doesn't make any sense. You have to specify the observer. And only then does everything tie together. Only then does all of this make any sense at all, is the whole theory consistent.

You have to always mention the observer. If you don't mention the observer, then what you're saying is just not meaningful. It doesn't make any sense at all. Yes?

AUDIENCE: [INAUDIBLE] If I were to take [INAUDIBLE] to school, [INAUDIBLE]

My school ends at, like, 3:00. So if I went to school, and my watch said 3 o'clock PM, [INAUDIBLE] 3 o'clock when I get [INAUDIBLE]

NICHOLAS DIBELLA: So that's kind of a devious thing to do. So you're proposing just if I just kind of arbitrarily set my clock to say 3:00 PM, and I'm sitting in school, saying, hey, teacher, look, it's 3:00 PM. Can I go? Is that a valid thing to do?

That's kind of unfair. that's kind of unfair. We have to first synchronize our clocks. We have to make them agree at some point in time.

So let's say that we synchronize them at 7:00 AM. Then if your clock says 3:00 PM, while your teacher's clock says 1:00 PM, then you might have an argument there. But what you're proposing is a little unfair. And I can sense great lack of discipline in you, kidding.

So this time dilation effects is just one of many interesting features of special relativity. I'll leave that there. There are a lot of other interesting features.

For example, sticks like this, sticks actually get shorter when they move. So as I walk across the room, it actually gets a little bit shorter. Now, obviously, you don't observe it's at every day speeds.

But if this thing, if this eraser were moving close to the speed of light, then you would actually observe it to get smaller. And the faster you make it go, the smaller it gets, the shorter it gets. And, similarly, I forgot to mention that the faster the train goes, the slower the time ticks.

And so actually, as you approach the speed of light-- sorry, as the train approaches the speed of light, the rate of its ticking becomes slower and slower and slower. And as it approaches the speed of light, time essentially stops. The rate of the ticking becomes infinitely slow. You had a question?

So all these effects, this length shortening time dilation-- and there are others-- they only become noticeable, at least to us because we're used to living in a world where objects don't move very fast relative to the speed of light. So we don't have a hardwiring in our brains.

Our brains have a kind of common sense that things behave in a certain way under certain conditions. But there are many extreme conditions that we just haven't experienced. And our brains just can't really understand them.

So they're not noticeable. These effects aren't noticeable unless you're traveling close to the speed of light. Yes?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: It actually shortens its length. OK, it shortens its length relative to you. But relative to it, it doesn't get short. I know it's very weird.

But if you think hard, if you sit down and think about these two postulates, if you draw everything out, if you look at how light moves, and you look at the geometry of sticks and stuff, then you can actually infer this. You can actually infer these consequences.

And they're completely strange. But they're completely logical consequences of these two very simple postulates.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Yeah, suppose you can't see things that are very, very thin. Yeah, it would be so thin that, how are you going to see it? Now, time dilation has actually been observed many times.

At particle accelerators, we very routinely accelerate particle to 99.999& the speed of light, things like electrons, protons, and so forth. But every day objects like trains, they require a lot more energy to get them very fast. So we don't really observe trains getting shorter.

We don't observe the clocks to to tick much slower than ours. It just takes too much energy to get them to go fast. But we have definitely observed time dilation for elementary particles.

So that provides a lot of evidence for time dilation and special relativity. But actually for length and traction, it's just really hard to get big objects going at a substantial fraction of the speed of light. So I've never heard of any direct observations of length contraction.

But special relativity implies it should be there. And all of our evidence indicates-- every experiment we've done has been consistent with special relativity. So even though we haven't observed length contraction happen, this shortening, we definitely have good reason to believe that happens.

Now time dilation in special relativity actually provides you a way of traveling into the future. It's very simple. Here's how to do it.

So let's suppose this is Earth. That's Earth. And get yourself a spaceship, just your average spaceship that can travel 99.99% the speed of light.

Yeah, it doesn't exist, at least today. It might exist in the future. Not even close, in fact, I looked it up. The fastest we've been able to get of any manned spacecraft to date has been half of a percent of a percent the speed of light.

But in any case, let's suppose we get a spaceship that can travel very fast. So here's a way of theoretically traveling into the future, a substantial amount into the future. So you have Earth.

Leave on your spaceship, travel very fast this direction, and then come back. You go very fast both of the ways. Now, because of this time dilation effect, let's suppose we're sitting on the Earth.

Let's say we're sitting on the Earth. And we have our clocks. And if we measure how long it takes for the spaceship to make its trip, to go all the way to some point and then come back, let's time. Let's see how long it takes.

If we're very patient, if we're willing to let this space ship go very far, we might see that it takes 100 years for the space ship to make this trip. But because of time dilation, as 100 years passes by for us, a smaller amount of time will pass by for the spaceship. So while 100 years passes by for us, maybe 10 years passes by for the spaceship to make this whole journey. Yes?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Yeah, they'll only age 10 years. Now, this actually presents a kind of paradox, because I said before that time dilation is actually symmetrical, that relative to me you guys are moving. But relative to you, I'm moving.

I say that your clocks run slow. You say that my clock runs slow. But here, I'm claiming that actually, as 100 years passes by for Earth, only 10 years passes by for the spaceship, once the whole thing is over.

Couldn't you say that relative to the spaceship, the Earth is moving? And so the clocks on the Earth will move slower. So 100 years passes by the spaceship. Only 10 years passes by for the Earth.

Couldn't you say that? But once everything is said and done, once the spaceship returns back to Earth, they're either going to be the same age-- the people on the earth are either going to have measured some time interval that's equal to the time interval measured by the people of the spaceship. Or they'll measure something else. Maybe they'll measure a longer interval or a short interval.

At the end of the day, one of those three possibilities has to happen. One of them has to be right. And it turns out that the right one of those possibilities is actually that the people on the spaceship age less.

And I'll leave that as a mystery for you right now. I'll let you think about how this paradox actually gets resolved. I said before, special relativity, these effects are symmetrical. But here, there's some kind of an asymmetry.

There's some kind of a paradox. But for some reason, which you have to figure out-- I'm not going to tell you today-- but for some reason, there's an asymmetry.

AUDIENCE: Do they know why?

NICHOLAS DIBELLA: Excuse me? Oh yeah, I know why. Yeah, we know why. Yeah, there's something very special about this little method that I mentioned that's responsible for the asymmetry. Yes?

AUDIENCE: You said that throughout the whole thing, [INAUDIBLE]

NICHOLAS DIBELLA: Yes.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Well, I mean over here, you, in fact, do slow down. You have to actually turn around. That's actually the resolution to the paradox.

So when you go in your spaceship, and you travel very far away and then turn around, you actually have to decelerate. Once you get to this point, you have to eventually turn around. So you have to actually slow down and turn the other direction.

So you're not actually an observer that's moving at a constant speed. You are actually accelerating that little bit over there. And because of that, special relativity doesn't apply to you.

It doesn't apply to you, the accelerated observer. And so that's responsible for the asymmetry. That's the resolution to the paradox.

Special relativity can deal with accelerated motion. But you just can't be the observer that's doing the accelerating. I can sit here, and then evaluate how long the accelerated observer will see his clock tick. I can evaluate that.

But I just can't be an accelerated observer when I'm doing that analysis. Special relativity doesn't apply to me. But, yeah, that's the asymmetry responsible here.

So this is a very simple method of traveling into the future, in principle. You just get a spaceship, go out very far, come back. And then as some amount of time passes by for you in the spaceship, a longer amount of time will have passed by for the people on earth.

So you've effectively traveled into the future. And depending on how fast you go, you can travel farther and farther into the future. So if you travel at 99.99& the speed of light, I wrote it down.

As 10 years passes by for you in the spaceship, 1,000 years passes by for the earth, people sitting on the earth. But if you go even faster, if you go at 99.99999% the speed of light, then it might be that as a day passes by for you, a million years passes by for the people on earth.

That's just what relativity implies, in principle. So this is all very solid physics. None of this is controversial.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Excuse me?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Well, I'm not sure how many nines you have to add for that to be true. I haven't done the calculation. But you can arrange for any scenario to happen. In principle, you can arrange for any kind of future date to travel to, just by adjusting your speed.

If you travel fast enough, you can get far enough in the future, if you wanted to. You would just have to do the calculation to figure out. But this class is completely non-mathematical. So I'm not going to the calculation.

But if any of you have questions, I can show you the formulas. And you can play around with them, if you want. I can show you later, if you want.

So in principle, time travel to the future is very easy. You just do this. Laws of physics say, time travel to the future is totally possible. So it's not really a physics issue that's responsible for our difficulty in getting into the future.

It's really an engineering problem. Time travel into the future is really an engineering problem.

It's just hard to build stuff that can travel fast enough to get a significant amount of time dilation to happen.

Last class, when we talked about extraterrestrial intelligence, extraterrestrial civilizations, I mentioned some methods that extraterrestrials might want to use to travel across the galaxy to go very fast. So they might use something like an anti-matter rocket, or a nuclear fusion ramjet, or some other stuff.

And people have thought about theoretical ways of getting to very fast speeds, very high fractions close to the speed of light. It's just that we have a hard time building stuff tend to do that. Maybe in 1,000 years, this will be feasible.

I don't know. I'm not going to try to guess at our future technological evolution. Yes, in the back?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Warp drive, that actually has to do with curving space and time.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Yeah, there's kind of a folding of space and time that goes on. I'll talk about something similar actually later, when I talk about wormholes. It's similar to that. That has to do with general relativity. Yes?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: How do I travel to the past? That's what I'll talk about after the break.

AUDIENCE: [INAUDIBLE]

--keep the same speed. So you wouldn't have to slow down on [INAUDIBLE] the whole time. [INAUDIBLE]

NICHOLAS Oh, so actually when you're moving in a circle, you're actually accelerating. OK, your speed

DIBELLA: isn't changing. But your velocity is changing.

So, actually, to be more precise, when I said everybody, you have to be moving at a constant velocity, not just constant speed. Velocity is speed, plus direction. So when you're moving in a circle, your direction is constantly changing.

So you're actually accelerating when you're moving in a circle, when you're rotating. Yes?

AUDIENCE: [INAUDIBLE]

Which one would be faster, and which would be slower?

NICHOLAS DIBELLA: I forgot. So the question is, which one-- so in a spaceship, the clock on the front, versus the clock in the back, how do the two readings compare to each other? It turns out that they actually don't show the same time. They're actually not synchronized with each other.

I forgot which one trails which. But they're actually not synchronized with each other. They're off by a little bit.

They don't show the same time, which is also unexpected. Yeah, there are a lot of unexpected things. Time dilation, I mentioned lengths gets shorter. Synchronization gets off.

Things start out synchronized, but they're no longer synchronized. Simultaneity is also relative. The fact that if I observe two things that happen at the same time, two things happen simultaneously, that you actually won't if you're moving at some speed relative to me.

Relativity is very strange. It has lots of strange consequences, lots of things that run counter to our common sense. But if you work through the details of these two postulates, you get all of them. Yes?

AUDIENCE: If you reverse the rotation of the Earth, would you go back in time?

NICHOLAS DIBELLA: If I reverse the rotation of the Earth like Superman, would I turn time backwards? No, but he was actually-- maybe he was traveling faster than light. Now, if you travel faster than light, then you could actually theoretically maybe travel back in time.

AUDIENCE: [INAUDIBLE]

NICHOLAS Yeah, so tachyons, these particles that I mentioned earlier, they theoretically travel faster than

DIBELLA: light. Special relativity would actually imply that they travel back in time.

So, yeah, they actually travel back in time. We have no idea if tachyons exist. There's a lot of theoretical problems with them. They're purely hypothetical. Yeah?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: So if they're going back in time, then do you eventually get back to the beginning of time, like to the Big Bang? And then what happens after that?

Yeah, I don't know. I don't know. I have no idea. Tachyons to start off with, they're on questionable foundations. So any questions you ask about them, you might get funny answers. And you might not be able to answer them.

I don't know. Yeah, that's a good question, though. Question?

AUDIENCE: [INAUDIBLE]

--moving at a higher speed at one point in its revolution. So that would-- it's moving at light speed so [INAUDIBLE]

NICHOLAS DIBELLA: OK, so I cheated a little bit. Thanks for keeping me honest. So I'm assuming the Earth is at rest. In fact, Earth is actually rotating.

It's revolving around the sun. It's actually rotating about its axis at a 24 hour period. So actually, the Earth is actually not the type of non-accelerating inertial observer that special relativity needs. But it's approximately good.

For the speeds involved here, it's definitely negligible. The rotation and the revolution, it's negligible. You can assume that it's essentially at rest, or moving at constant speed. You can assume that.

Any more questions about traveling to the future by this method? OK, we'll take a five minute break. Then I'll talk about time travel to the past.

Yeah, there's a very simple formula. So suppose the guy sitting, the guy we assume to be at rest, suppose he measures-- so he sees two events happen. And then he measures on his watch how long the time interval between the two events.

And let's say he gets some number. He gets t zero. Let's suppose that that's the number that he get. And now, let's suppose that the train was traveling at some speed v relative to him. So the train travels at some speed v.

And then you ask, what's the time interval somebody on the train gets between the two events? You ask, what is that time interval called t? And call the speed of light c.

And it turns out, you can prove this, that t equals t0, divided by the square root of 1 minus v squared, over c squared. So you can play around with that, if you want. And you can derive it through pure geometry, just based on these two postulates.

I mentioned earlier that the way we define time is kind of operationally. So one way you can define time is just suppose you have some box. Just see how long it takes for time to go up and down.

Maybe have mirrors. How long it takes for light to go up and down, you have kind of a light clock. So we can imagine installing some kind of light clock inside of a train.

And then ask, suppose one bounce up and down happens for somebody on the train. Then based on the fact that the speed of light is the same for everybody, how long should it take for somebody sitting on the bench? You could just work through the geometry, and you'll get that.

It doesn't take very long to show it. But it takes a while to get used to this kind of thinking. But you can basically derive this formula in less than five lines, just in a few steps.

And then there's a similar formula for lengths, how short they get, depending on how fast you're moving. For length, all you do is you move this quantity from the denominator to the numerator. It turns out that this 1 over the square root is always greater than 1.

So moving clocks ticks low. So as some amount of time-- yeah, so since they ticks slower-- you have to think about it to see why it makes sense. It all works out.

Up to now, I've just talked about time travel to the future. Special relativity just seems to allow time travel to the future, however much we want in getting as far into the future as we want. I mentioned briefly the possibility of using tachyons to get to the past. But nobody has any idea if tachyons exist.

So forget about that. So while special relativity doesn't seem to offer any possibility of getting to the past, general relativity actually seems to offer some hope that you might be able to get to the past. I should mention from the start that nobody in the world knows if it's possible to travel back in time.

Nobody knows. Nobody has any. Idea everybody agrees that the method I just talked about with the spaceship, time dilation through special relativity, everybody agrees that that works. That's completely uncontroversial.

But nobody has any idea if it's possible to time travel to the past. But people have come up with ideas that might work. It might not work. They're just ideas.

And all these ideas generally rest on general relativity. So I mentioned earlier that special relativity just applies to observers who are moving a constant speed. But general relativity actually applies to observers that are accelerating.

So if I start out and start moving at faster and faster speeds, then I'm an accelerating observer. And then I'd have to use general relativity to talk about events, to talk about time intervals, and spatial intervals, and so forth, and talk about physics. Also, if I'm revolving, if I'm rotating, then I'm an accelerated observer. And I have to use general relativity.

So according to general relativity, space and time are best thought of not as different things, but as different elements of an underlying spacetime. So this is that space and time are unified in an object we call spacetime. Now, according to general relativity mass curves spacetime.

So spacetime is just this object that space and time are part of. They're like different sides of the same coin. They're fundamentally different.

But you can't think of one without the other. They're attached to each other. So that's what space time is.

What does it mean that curve space time? Well, we say that when there's mass presence, space time gets curved. The more mass you have somewhere, the more space time is curved there.

So special relativity, not only does it not deal with accelerated observers. But it also doesn't deal with gravity. And there's actually a very deep connection between gravity and acceleration. It's called the equivalence principle that Einstein discovered.

It actually says that gravity and acceleration are actually equivalent to each other, in a certain sense. And it was actually-- Einstein said it was like the most brilliant insight that he ever had. It was his happiest moment in life, when he had that insight, that acceleration and gravity were actually the same.

But I can't really get into that, because I want to explain how this works. But so special relativity doesn't deal with acceleration. It doesn't deal with gravity. But general relativity does.

So we say that the space time of special relativity is flat. It's called a flat space time. And everything that I said earlier is true just in flat spacetime, the way that all that stuff works.

In curved spacetime, things are very different. In curved spacetime, there is another kind of time dilation present. It turns out that the closer you are to a massive object, the slower time goes for you.

So suppose this is the earth. If you're on the surface of the Earth, time goes slower for you here that it does for somebody over there. So maybe as an hour passes by for somebody over here, more than an hour passes by for somebody farther away.

So the greater the gravity, the more curve the spacetime, and then the more time will be stretched, the more time we will be dilated. So this is called gravitational time dilation. Do any of you sleep on bunk beds, maybe a brother or sister? Once?

I used to. At some point in your life, some region of spacetime in your life, me too. I shared it with my younger brother.

So he would sleep on the bottom. And I would sleep on the top. So gravity is greater-- as you get closer to the center of the Earth, gravity increases. So the gravity is greater on the bottom bunk than it is for the top bunk.

So my brother actually aged less than I did during those years that we shared the bunk bed. But as I said, here's three years younger than me. And so I've had three more years to waste my life to mess up, to screw up in life. And he's the one gaining the extra time over all these years.

Now that I've thought about it, this is very unfair. I should have been the one on the bottom. He's been getting this time, all this extra time. It's unfair. And now studying general relativity, I have this outrage.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Yeah, so the difference in time is completely unmeasurable. The difference in gravity is completely unmeasurable. So the difference in time is completely unmeasurable.

But, in principle, it's actually there. You just can't measure it. It's actually there. It's a little element of reality that you can't actually see. But it's there. It's inside of nature.

So did you share the bunk bed with a brother? You were younger? Yeah, we need to educate the next generation of brothers, and get things right. One day, I shall seek revenge. Maybe I'll travel back in time and take care of it.

AUDIENCE: So the way spacetime occurs [INAUDIBLE]

Is the universe then longer? [INAUDIBLE]

NICHOLAS DIBELLA: Oh, so--

AUDIENCE: [INAUDIBLE] --much, much longer time.

NICHOLAS DIBELLA: So when I talked about the age of the universe in the first couple of lectures, I had a particular kind of observer in mind. So whenever we make these observations, we have to first synchronize our clocks. And we have to have some kind of frame in which everything is measured in.

And I mentioned the existence of this microwave background that's always out there. And the way that-- so the time that I was mentioning, the way that we synchronize our clocks, the way we keep track of time, at least the very natural way of doing it, is to just synchronize your clocks based on what the temperature of the microwave background is. So if it's at a certain temperature, you say it's a certain time.

And so this is one particular type of observer. It's a very natural type of observer, because the microwave is out there. And when it's a certain temperature-- you also want it to look uniform, a certain temperature, and look reasonably uniform and isotropic, the same in all directions. When you do this, then you have a kind of natural reference frame, we call it.

And that's the reference frame that I had in mind when I was talking about the age of the universe. But, yeah, so time will pass by for other kinds of frames, for other kinds of observers. But they won't be any longer than that, it turns out.

They won't be no longer than the one that I mentioned. It's called the co-moving observer. They won't actually be any longer than that. They might be shorter. But they won't be any longer than that.

But it's always important to say, who's doing the observing? This is the time as measured by who? Who measures it? Good point.

So this is called gravitational time dilation. And if you think about it, this actually provides another way of traveling into the future. I'll get to the past in a minute. But this actually provides another way of traveling into the future.

So what you can do is you can get a very massive thing, like maybe a very massive star, or a black hole. I won't go into black holes. But black holes can be very massive. And if you sit near the edge of where the object ends, like if you had a very massive star, you sit over here, then time goes slower for you here than it does for somebody over here.

So all you need to do is find a very, very massive thing, build it or something, I don't know. Get a very, very massive thing, sit at the edge of it, and just wait a little bit. Just wait a while.

Depending on the mass of this thing, and depending on how far away something else is, then as some amount of time passes by for you, more of amount of time will pass by for them. So you can arrange it so that-- if you're an engineer who can do anything, if you're a god engineer, then you can arrange it so that as a day passes by for you, a year passes by for them. So you can also use gravitational time relation to travel into the future.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Well, actually, at the center of a black hole, time and space cease to exist. If I have time at the end of class, I'll talk about black holes for a couple of minutes. But now, I want to talk actually about something even more interesting than black holes. They're called worm holes.

So over the years, people have proposed a number of ways of traveling back in time. Nobody knows if any of them can actually happen. But today I'll talk about one of them. It involves something called a worm hole.

So let's imagine, just for simplicity, let's imagine that space is two dimensional. It's like a sheet of paper, just to help us visualize things. Just imagine space is two dimensional.

And we can imagine looking at space from the side. So we can imagine-- suppose this is all of space. You can imagine looking at it like this. So it looks like that.

General relativity allows for the possibility of these things called wormholes, which actually connect two points in space like a tunnel. It's not just any kind of a tunnel. It's actually a shortcut between these two points.

So this is the space-- I mean, you might be wondering why this is curved. I've been talking about curved spacetime. So maybe you could think, well, maybe that's why it's curved. No, don't worry too much about it.

But general relativity actually allows for the possibility of making things, we call them warm holes, that can actually connection two distant points in space. So while it might take-- let's get realistic numbers. While star Sirius is about 54 trillion miles away.

It's very far, 54 trillion miles away. If you traveled at the speed of light, which is very fast, then it would take you nine years to reach it if you just traveled in the way that we usually travel. It would just go from here to there in a straight line. It would take you nine years to reach Sirius.

But if the Earth and the star Sirius-- let's say the Earth is right here and Sirius is right here. If the Earth and Sirius are connected by a wormhole, then you can theoretically create a wormhole of any size. And you can make a shortcut between these two points.

And while this whole thing might be 54 trillion miles the usual way, I'm not drawing it to scale, this wormhole might only be 10 feet long. General relativity allows for the possibility of these really weird things, these shortcuts in space. They're called wormholes.

Now, the way that time travel to the past would work is like this. So the wormhole has a couple of mounds. And the way to get from one mouth to another is you just go inside of it.

So you find the wormhole. You make it somehow. I'm not going to I try to say how to make a. Wormhole but general relativity allows for their existence. And some people have thought of ways of making it.

So let's just assume that they can be made. You could, in principle, find the mouth of the wormhole, go inside of it, then come out, and get to the star, make the shortcut.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: It might be 10 feet across. So you can travel whatever speed you want. You could walk, or you just hop in it. Or maybe it might be in front of you, and you just dive in it. It might be something like that.

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Have I seen what?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: I only have a few more minutes to describe this. So here's how time travel to the past would work. So you take one of these mounds.

And you accelerate it. You get it to a very fast speed, maybe like 99.99% the speed of light. Yeah?

AUDIENCE: [INAUDIBLE]

NICHOLAS DIBELLA: Maybe, but for now, don't worry about that. I only have a couple more minutes to describe this. So the way you time travel to the past, you take one of these mounds.

You get it to go very fast, maybe go this way. You get it to go very fast, and then bring it back. In principle, this kind of thing might be possible, similar to what we did with the spaceship. Remember, we took the spaceship, made it go out, made it come back.

And if you do this, then general relativity actually says than, that outside of the wormhole, if you do this, then this mouth will age less than this mouth sitting over here. I mean, you only move this mouth.

This mouth stays at rest. It says stationary. So while this mouth might age five years when you move it very far, very fast that way, then bring it back this way, this just ages five years, this mouth might age 10 years. And this is what observers outside of the wormhole will agree on.

That's what general relativity says. So general relativity says that the two clocks there and there will disagree if you're outside of the wormhole. But if you're inside the wormhole, the general relativity actually says that these two times, the times for both mouths, they have to always be synchronized. They have to always agree.

Very peculiar feature of general relativity, they have to always agree. So here's a possible way that you can travel back in time. So you get this mouth to move back and forth very fast so that to outside observers, observers outside the black hole-- sorry, the wormhole, this has only aged five years, while this has aged 10 years.

So you've done that. You move the wormhole back and forth. And then you jump inside the wormhole. You just go inside of it.

Or let's say you're accelerating with the mouth, so with five years that way, five years that way. Then you just hop into the wormhole. And what general relativity has to say is that these two times have to agree. So once you've hopped into the wormhole, you're automatically seeing these two times agree.

So five years has passed. Maybe it was the year 30000 when you started this whole thing. So it's 3005 when you put it back together. It's 3010 here.

So you can hop into the wormhole. And once you're inside of it, it will be 3005 again for this mouth. And so once you hop out of it, once you jump through it, you travel back in time to somebody over here, to an observer over here.

It sounds very strange. And I don't know of any way to understand it intuitively. But if you work through the math of general relativity, it says that this is what happens. It just says that that's what happens.

Now, there are a lot of problems with this method. For one, we have no idea if wormholes are even possible to create. We've certainly never seen one. We've never observed one before.

It might be impossible to create. Another problem is that wormholes are actually unstable. So once you make them, it immediately falls apart very quickly, at least if you make it using ordinary matter, if you create it using ordinary matter.

But it might be possible to stabilize a wormhole using what some people call exotic matter. And this is matter that essentially has negative mass, which is weird. So you need some kind of a weird material to stabilize it, or else it's just going to fall apart on you.

And if it falls apart on you, space and time will cease to exist. And who knows what happens to you? Another problem is that you might actually need a time machine to make a wormhole. You might need a time machine to make this kind of a time machine.

Nonetheless, if you can get around these difficulties, then theoretically it might be possible to travel back in time, maybe. Nobody really knows if it's possible. Most experts, I think they don't think it's actually possible to travel back in time with a wormhole.

But people have proposed other things, like warp drive, and other weird things that exploit that curved geometry of spacetime. But today, nobody knows if time travel to the past as possible. Time travel to the future, definitely, everybody agrees on that.

Everybody even agrees on this. This is very well established. We've actually measured gravitational time dilation.

Wormholes and more speculative ideas, nobody really knows. But if he can conquer these difficulties, then the laws of physics say that, well, the past might be yours. The future definitely is yours.

In any case, it's good to know at least physics gives us some hope that it might be possible. Time travel might be possible. 100 years ago, nobody thought that any of this business would be scientific. It didn't make any sense to think about it scientifically.

But today, these are actually topics that people actually work on, that researchers actually work on. So it's really become a real scientific topic, this big question of time travel. OK, see you next week.