[SQUEAKING]

[RUSTLE]

[CLICKING]

PROFESSOR: Welcome back to 8.20. In this section, we're going to talk about time, timekeeping, and how to relate time between two different reference point. Now, let me start with a quote by Albert Einstein. "Everything should be as simple as possible, but not simpler."

So let's start with this in mind. And recall that we ended the last section by finding that the wave aether model doesn't really describe electromagnetic waves very well. We see that there is a problem between the experiments, specifically the one by Michelson-Morley, and the theoretical picture people had in mind.

So Einstein approached this in an interesting way. He simply postulated the things he thought need to be true. He said, "The same law of electrodynamics will be valid for all reference frames where all laws of mechanics hold good. This is the principle of relativity." The second postulate is that "Light is always propagated in empty space at the velocity 'c,' independent of the state of motion of the emitting body."

So with these two postulates, we will now derive the theory of special relativity. And again, we'll start by talking about time. So time is suspect. And I alluded to this already when we looked at Galilean transformation, where it simply, out of our intuition, assumed that time is invariant.

Now, when we now talk about time, the viewpoint I would like you to have is that we want to look at clocks from different reference frames. We want to investigate whether or not events happen simultaneously or not. What does it mean?

When we make a statement like a train arrives at 7 o'clock, what we mean is that there is a simultaneous-- two simultaneous events happen. One is that this little clock here shows to point at seven and 12, meaning that it indicates to us that-- this event indicates to us that it's 7 o'clock. And the second event is that the train actually arrives at the station. So those two events happen simultaneously.

The question now is whether or not two observers, one stationary and one moving, agree with this observation. And I take it away-- the answer is no. There is a relativity of simultaneity, meaning that two observers can very much agree on the description of two events, but not necessarily that those two events happen simultaneously.

So let's investigate. And we use our two friends, Alice and Bob, in order to have this discussion. All right, so we start from a situation where Alice and Bob are both stationary.

Alice is on her spacecraft, and she has a device on her spacecraft which shoots light or paint balls towards two clocks. And each time this happens, the clock ticks, right? And we just look at one situation. So she has a clock on the left and a clock on the right.

Bob observes Alice's clock. And he can compare this observation of Alice's clock with his own. So in this station, as to duration, there's a TA and a TB. Those are the times of Alice and Bob. Both are 0. This is when the situation starts. And the capital T indicates for Alice and for Bob when they observe that the clock has been hit.

I should add here that when we talk about observation in this entire class, unless I make a very explicit exception to this, we don't consider the fact that observing actually means that light has to be emitted from the clock and enters Bob's eye in order for him to conclude that there was something happening. The observation is like taking an instantaneous picture. OK, so we have to keep this in mind. But in this simple situation, nothing is moving. We can hopefully agree that the times being read for Alice and Bob on the left and the right clock are all the same.

Now, we go in the second situation, where we use the same device but with a paintball. So now, Alice moves and Bob is observing her. She moves with a relative velocity, v, and shoots off the paint balls with a velocity, u. The velocities will add, meaning that the answers to clocks are initially synchronized. So there is a small tA equals small tB equals 0.

Once the clock hits, you can hopefully agree that Alice and Bob will agree that the times when the left clock and the right clock hit are the same, right? But now, we want to enter the situation where we use light. So we use a phaser in order to do the very same.

So Einstein just postulated that the speed of light is constant, is c. And it's the same in all reference frames. And it's independent of the emitter, which means that we cannot add the velocities anymore. So the velocity, as seen by Alice, of light is c.

The velocity of the same light by the moving observer, Bob, is also c. So here, we can conclude that the times for Alice for where the situation is stationary, both clocks will hit at the very same time. Those two events, clock one and clock two are hit are simultaneous.

Why, for Bob, this is clearly not the case. You can see here that this lagging clock is being hit first, while the leading clock is hit a little while after. So if Bob and Alice now meet and they discuss whether or not those two events happened simultaneously, they will disagree. For Alice, those two clocks were hit simultaneously-- at the same time for her. But for Bob, the first clock was hit first and the leading clock was hit second.

All right, we can conclude the two events can be simultaneously to one observer but not to another one. This is rather confusing. And we will see and use this fact a few times later on when we discuss the famous paradoxes of special relativity.

So let's look at this in a concept question to just make sure that we're all on the same page. Again, we discuss your diagram three. Alice move to the right. Bob is the observer. Alice's fires her phaser at times equal 0. Then the situation unfolds.

At time TA, capital TA, Alice observes that both blocks are hit. At time TB1, Bob observes that the left clock is hit. At time TB2, it's the right clock. Which of the following answers is correct? So here, you want to stop the video and think about which of the answers is correct.

So moving forward, the correct answer is number three, where TB1 is smaller than TA is smaller than TB2. So again, the leading clock lags. The leading clock has a larger TB, which means that clock ticks a little slower. And again, the two events, they can be simultaneously to one observer-- Alice, in this case-- but not to another, Bob.

All right, let's look at clocks a little bit more and design an optical clock. So here, the situation is as follows. We have two mirrors in which we inject light. The light travels up and travels down. And that's what we call one clock tick of this optical clock. The length between the two mirrors is L.

So for Alice, she has this clock in her hand. And she can happily observe the ticking of the clock. OK, Bob observes Alice's clock and compares it with his own identical clock. There's a relative speed between Alice and Bob, and that's v in x direction.

Now, the task for you is to relate the clock ticks which are observed by Bob and the ones which are observed by Alice in Alice's clock. So again, stop the video and work out the algebra. The answer is going to be, again, surprising.

So if you do this now, we find this picture. So we calculate how long does a clock tick take. The light has to travel to L with a velocity c. So the clock tick is 2L over c. The length can be expressed as c times t delta tA over 2.

For Bob's, the situation is a little bit more complicated. And we have to use Pythagoras in order to calculate the length. So we define that the length the light has to travel is D, then the delta tB as Bob observes this is 2 times D over c. Again, for Bob, the light travels with the speed of light. Einstein just postulated it. And then we find the length as expressed to the time as c times delta tB over 2.

The length in x is simply given by the relative velocity, v, times the time it takes for the clock to tick-- v times delta tB. So then we can express D square via L squared plus x squared over 4 and use those expressions here. So we just use this for L, this for D, and this 4x, we find this expression here. All right.

And then we solve this for delta tB. And we find the relation between delta tB and delta tA and can find that it's 1 over square root 1 minus v squared over c squared, which is the Lorentz factor. So we just used a simple clock and Einstein's postulate derived time dilation. We find that for Bob, Alice's moving clock moves slower. Great.

So again, gamma is 1 over square root 1 minus v squared over c squared. We often use, in short, beta as a relativistic velocity. It's unitless and defined as v over c. gamma is always greater or equal to 1. And it's mostly one for everything we observe in nature.

So in one of the p sets and also here, I invite you to simply calculate values for gamma for things you might think are fast-moving objects. So we start with a fighter jet. We look at the International Space Station, the Earth around the sun, the particle which almost moves with the speed of light, and the proton at the Large Hadron Collider, which is only 3 meters per second slower than the speed of light. So again, stop the video and work out those numbers. You will need a calculator for that.

So if I do this, I find for this very, very fast F15 fighter jet, which moves with speeds of 2,680 kilometers per hour, that the number for gamma is 1.00000000000, which is 11 zeros, 3. So we find this very, very small number or number which is very, very close to 1. The duration for the International Space Station changes a bit-- only 9 zeros.

For the Earth around the sun, the Earth is really, really fast, travels a long distance. Every year, we travel once around the sun. And you know, every year you get older. You have a lot of mileage on your back. Here, you have eight zeros.

Particle which moves with 0.9 times the speed of light, here the gamma factor is very different from one. It's 2.3. And the protons we have at the LHC, they have a gamma factor of 7,000. So you see, once you get close to the speed of light, the gamma factor approaches large numbers. And that's where our relativistic effects really are visible.