[SQUEAKING]

[RUSTLING]

[CLICKING]

MARKUS KLUTE: Welcome back to 8.20, Special Relativity. So in this section, we're going to review the content of the material, but underlined with a few questions and examples, very similar to the previous section. It's just this one is interleaved with activities.

So let me start by bringing back two of those Einstein quotes, which nicely relate to each other in a sense that they feed off each other. The first one is, "I have no special talent. I'm only passionately curious." Albert Einstein. And the second one, "It is a miracle that curiosity survives formal education." And I [LAUGHS] sincerely hope that I didn't stop your curiosity with this lecture-- quite the opposite.

Like we discussed here, it's just the starting point of a wider discussion of general relativity in your education at MIT in the Physics Department. You could learn about quantum mechanics, quantum field theories. And a lot of physics is out there, which is super exciting and interesting. So it basically needs your curiosity in order to tackle challenging questions in physics today.

We started the discussion looking at the background which led Einstein to make his discoveries. And specifically the year 1905, in which he was able to come out with five papers, all breakthrough papers, including the theory of special relativity.

His career didn't stop there. He developed the general theory of relativity and published a paper on this in 1915. And his fame as a physicist really comes out of the predictions he made at that time.

So we set the context of this class, and we started with a question of Galilean transformation and whether or not you can tell in a moving train car whether or not this is actually moving or stationary. And we demonstrated that time and acceleration is invariant in the Galilean transformation. And then, therefore, since you cannot distinguish the strength of a force in two reference frames which move to each other with moderate velocity, you cannot tell whether or not the train car is moving or not.

Very important are the development of clocks and times and signal processing of the time. And we discussed this in the context of trains and train lines, but also in Einstein living in the city of Bern, with a large number of clock towers which needed synchronization. And even working in the patent office certainly confronted him with those questions all the time.

So time is suspect. That is really the key to moving out from Galilean transformation into Newtonian mechanics to special relativity.

When we classify or when we look at specific series, we have to understand that they live within a context, within a range of validity. And so classical mechanics is not wrong because it breaks down at large velocities. It's just only correct in the frame of slow velocities. And special relativity also has its limitations, as in it only describes reference frames or scenarios in which there is no acceleration between two reference frames.

Going back to the question of the time, Michelson-- and a number of other experiments leading to the very same direction-- was trying to establish that there is an ether wind, a medium in which light is moving. And his experiment, at the time, failed to demonstrate that ether actually exists.

His experiment used a light source and a couple of mirrors in order to show interference patterns. And those interference patterns didn't manifest themselves. So he thought for a long time that his experiment is limited or that he has made a mistake. But it turns out that ether indeed doesn't exist.

Einstein tackled this problem by making two postulates. The first one is the principle of relativity, that there is no preferred reference frame if you want; and the second, that the speed of light is constant-- and constant and the same in all reference frames. And in this class we use those two postulates in order to derive everything we know about special relativity.

So we looked at the implications. And the implications started from time dilation, length contractions. We were able to derive the Lorentz factor and Lorentz transformation. And we did this by showing this light clock here, where you observe a ticking clock in which there is two mirrors and light bouncing back. And each time there is a bounce, we count this as one tick of the clock.

So if the clock is moving, the light has to travel a longer distance. And hence time is delayed. And from just the geometry of this problem, we were able to derive this gamma factor here-- 1 over square root of 1 minus beta squared. The beta is velocity over the speed of light.

So as the first activity in today's class, I want you to think about a clock which is moving with a photon, a clock which is moving with the speed of light. And also discuss why isn't it possible to go faster than the speed of light. And why can you not just keep accelerating? So think about this a little bit. In the live class we will have a discussion. But just come up with some sort of answer of why this is the case.

So here we have, in the class, actually showed that there is a real speed limit, that if you try to go faster, past [INAUDIBLE] velocity, you run against a boundary, a real speed limit. If you think about keeping accelerating, giving more energy, you find that the amount of energy you need in order to go faster and faster, faster, doesn't get you to velocities which are faster and faster. And again, you enter a speed limit-- the speed of light.

An important topic in understanding some of the paradoxes in special relativity, and some of the confusion, is the concept of the relativity of simultaneity. Now, it can be illustrated quite nicely in this example here, where you have a carriage train car with light being emitted and clocks which record those events at each end of the train car.

For the stationary person, those clocks will tick in sync. They will always show the same tick and the same time. But for somebody who's observing this train from a platform, or somebody who's moving with a relative velocity towards this train car, you will see those clocks not ticking at the same time.

So the clear evidence is given in this picture again, where you see that the light's being emitted in the center, but one side of the train car is hit first and the second side is hit afterwards. So you see that the leading clock lags. The leading clock in this example lags behind.

And so what you find here is that events which are observed simultaneously for one observer-- in this case, the person inside the carriage-- they will not be simultaneous for an observer who's moving with a relative velocity.

And that led us to the understanding of the pole in the barn paradox, where, in one example, the event of the front of the pole hitting the back of the barn and the event of the back of the pole hitting the front of the barn, they are simultaneously for the barn owner.

But they're not simultaneously happening for the person who's carrying the pole. In this case, the event of hitting the back of the barn is simultaneous to an event where the back of the pole is still sticking out of the barn.

So there is a clear disagreement. But the disagreement can be resolved by understanding that simultaneous events are not necessarily simultaneous to two observers.

Then we moved on to a variety of other paradoxes in special relativity. And the most famous likely is the twin paradox, where we discussed that a person moving away and then returning is younger than the person who actually stayed at rest. And we discussed that we were able to use time dilation or length contraction in order to quantitatively figure out the difference in time.

But we also discussed that the person who is moving away and then coming back needs to describe the journey in two different reference frames. And from the fact that you don't consistently can describe this sequence of events as two reference frames can see the paradox and the extra confusion.

So here we have another activity-- an asymmetric travel. So we discussed also the example where two people move away and then they come back in a symmetric fashion. But here we want to discuss the case where there are three trends.

Carol stays on Earth. Bob moves to Star 1. And Alice moves to Star 2. The distance to Star 1 is longer than the distance to Star 2. So the question is, in this journey, they both start and they both return at the same time for Carol. But which of the twins is the youngest?

So again, I invite you to just work this out. You can use some numbers if you want a quantitative answer. Or you can just reason about [INAUDIBLE].

The answer here is that Bob is the youngest of the three once they return to Earth. And the reason for this is the distance he has to travel is the longest. Hence the velocity he has to travel in is the largest. And hence the effect of time dilation for him is the biggest. And therefore he's going to be the youngest of the three.

All right. We had a rather long discussion about waves and light, Doppler effect, and relativistic Doppler effect. Here, just as a reminder, the wave equation for an electric field in a vacuum. And the solution to the wave equation is use the second derivative with space and time. And the solution simply can be expressed as a cosine, which is a function of space and time.

We have talked about light quite a bit. And just as reminder, [INAUDIBLE] the energy of photon is related via the Planck-Einstein relation to the frequency. So the higher the frequency, the higher the energy. The higher the frequency, the higher the energy.

And here, in this picture, you can see the effect of the Doppler effect, where, when you have a moving source, the observer sees the waveline modified. Objects which move towards us are blueshifted, starting from white light, or green light in this example. And objects that move away from us are redshifted.

The effect can be used, for example, in speed measurements of cars. It can also be used in order to measure speed or distances of stars moving away from us. And so that defines, then, the concept of redshift, which is simply the ratio of the difference in wavelength divided by the wavelength as observed by the observer.

So here there's two concept questions. The first one is, is the wave equation, which you can see there as an example, invariant under Lorentz transformation? And the second question is, how about the solutions? Are the solutions to the wave equation invariant under Lorentz transformation?

So I'll have you work this out again. And the answers are yes and no. The wave equation is invariant. The wave equation describes the physics. It explains how electric and magnetic fields change. And the laws of physics need to be invariant under Lorentz transformation. Otherwise they will not be valid. They will violate the postulate we just made that all reference frames are equal to each other.

However, the solutions of the wave equation-- light itself-- is not invariant under Lorentz transformation. We've just discussed redshift and blueshift, which means that the wavelength and frequency of light changes with respect to the observer, or for each observer. So the solutions-- light-- are not invariant under Lorentz transformation.

And then we went a little bit into particle physics. And I have to apologize for my own preference. But elementary particles, as they have been reproduced or observed, are typically moving at rather large velocities. So they are very good examples to study effects of special relativity.

We looked at energy, the total energy m0 gamma c squared, which also can be expressed as the energy of the rest energy of the particle, m0 c squared, plus the kinetic energy. And we looked at the total energy as being invariant, one of those invariants, as equal to the total momenta squared. The total energy squared is equal to the total momentum squared times c squared plus the rest mass squared times c to the fourth power.

And then we went through a larger number of examples, from accelerating electrons to composite particles. We talked about deuteron photon absorption and emission, the creation of particle, the creation of antiparticles, and the scattering of particles.

So here we had another example. Oops-- without the solution. In 1995, at Fermilab, a proton-antiproton collider, the Tevatron, top quarks were discovered. And we measured the top quark mass to 175 GeV. The center of mass energy at the Tevatron was 1.8, and later almost 2 tera-electronvolt, and clearly sufficient for the production of top and antitop.

But what is the minimal energy in order for this process to occur? And here we went through a number of examples. The minimal energy-- sorry. I have to work this out again. The minimal energy required can be derived or extracted in the center of mass frame, where the top and antitop are produced at rest.

And if you do this-- in this example, the proton in this collider experiment-- the experiment is already conducted in the center of mass frame. So the minimal energy is simply 2 times the top mass times c square, or 2 times gamma times the mass of the proton times c square, which gives you a gamma factor of 175.

But the likelihood to actually observe a top quark and a antitop quark at that energy, 175 GeV proton or antiproton energy, is rather 0. And the reason for this has to do with the structure of the proton.

The actual interaction between the proton and the antiproton is such that the quarks and antiquarks inside the proton, and also the gluons, interact. And they only carry a fraction of the momentum and the energy of the proton. And hence this minimal calculation is insufficient to get a sufficient cross-section likelihood for top quarks and antiquarks to be produced. But that is particle physics and goes beyond the scope of this lecture.

One last point, which leads sometimes to confusion, is the concept of conserved and invariant properties. When we look at the meaning of the word, invariant means never-changing. And in the concept of special relativity, properties are invariant when they do not change under Lorentz transformation or Galilean transformation, as we discussed earlier in the class.