Relativity

Transcript

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Time, light, mass, energy. These are some of the most fundamental properties in the universe and these are the properties that are explored and ultimately transformed by Einstein's amazing theory of Special Relativity.

Relativity is often thought of as one of the most complex theories in all of physics, but the fundamentals have actually been around for centuries. In fact, it all started in the sixteen hundreds with the basic study of motion.

Relativity was pioneered by Galileo Galilei, an Italian mathematician, philosopher, and physicist. Galileo asked some very insightful questions about the nature of motion. Particularly, he asked, "What does it mean for an object to be in motion and what does it mean to be at rest?"

These seem like pretty simple questions, so let's give ourselves a little test. Okay, was I moving, or was the spaceship moving? Most people would probably say that the spaceship was moving while I was standing perfectly still.

But Galileo realized that isn't all there is to understanding motion. Let's change the scenario slightly. Imagine that you were riding on the spaceship. From this perspective it looks like you and the spaceship are standing still while the earth and everything on it go flying by.

You see, in reality, there's no reason for us to believe that the earth is sitting still. In fact, the earth is spinning around its axis and flying around the sun at 67,000 mph! And our whole solar system is flying around the center of our Milky Way galaxy at around 490,000 mph! At some point, you come to realize that it looks like everything is moving unbelievably fast through space!

But Galileo realized that it doesn't make any sense at all to describe things as moving or sitting still unless you describe them as moving or sitting still relative to something else. To make this more clear, let's explore another example.

Imagine that two spaceships pass each other in opposite directions in the middle of outer space. They aren't speeding up or slowing down; they're just gliding in straight lines. If you were riding on the red spaceship, it would look like the blue spaceship had gone to the left. But, on the other hand, if you were riding on the blue spaceship, it would look like the red spaceship had gone to the right.

Both would be correct. It just depends on your point of view. Physicists would say that it depends on your “reference frame.” Relative to the red spaceship, the blue spaceship went to the left. Relative to the blue spaceship, the red spaceship went to the right.

Now this principle is called relative motion because it states that motion can only be described relative to some reference frame. And the nature of relative motion is such that the laws of physics are always the same for any reference frame. This is a crucial point: the laws of physics, whatever they may be, will always apply, no matter what reference frame you are in.

It’s very easy to test this. Next time you fly past Earth on a spaceship (or ride on a bus or a train, I suppose), throw something straight up into the air. Relative to you, it will go straight up and then straight down just like normal. At the same time, an observer back on Earth would observe it traveling on a curved path. Both of these scenarios are consistent with the laws of physics, even though they seem different in different reference frames.

So that’s the gist of Galilean relativity. But it turns out that the story doesn’t end there. Galileo was right, but he wasn’t completely right. The next big step wasn’t made until the 1900s when the German physicist Albert Einstein came along.

Albert was a very creative person and a very independent thinker. He believed that “the true sign of intelligence is not knowledge, but imagination.” He was also known to think very abstractly. He once said that “reality is merely an illusion, albeit a very persistent one.”

Albert Einstein contributed greatly in many areas of physics, but he is best known for his theory of special relativity. Special relativity is an amazing theory that lays the groundwork for our understanding of light, time, mass, and energy.

But Einstein didn’t just create special relativity out of the blue; rather, he discovered it while trying to resolve a perplexing conflict that was puzzling physicists at the time. You see, the principles of relative motion that we have just discussed were inconsistent with the newly developed theory of electromagnetism. Let’s take just a minute to describe electromagnetism and then we can see how the two theories were in conflict.

Electromagnetism is described by four equations, set forth by James Clerk Maxwell. These four equations describe the properties of light as ripples of sorts through the electromagnetic field. The equations said that these ripples must always travel at the same speed. They must *always* travel at 300,000,000 $^{m}/_{sec}$ (actually, they travel at exactly 299,792,458 $^{m}/_{sec}$ but it's a lot easier to just round up to 300,000,000). This is a fundamental physical law: $c = 300{,}000{,}000\ ^{m}/_{sec}$. We use c for the speed of light because it stands for "celer," the Latin word for swiftness, which is very appropriate because 300,000,000 $^{m}/_{sec}$ is unbelievably fast!

So as I was saying, Maxwell's equations and Galileo's relative motion were in conflict with each other. Now to see where this conflict arises, we have to construct a light clock. A light clock is just two mirrors with a beam of light bouncing back and forth between them. Since light always travels at the same speed, it must make contact with the mirrors at regular time intervals, just like a ticking clock.

Now let's install such a light clock apparatus on each of our two spaceship. Imagine that you were riding on the red spaceship as the blue one passed you near the speed of light. Now when the other spaceship passes by, you can see that its light beam isn't just moving straight up and down; it's moving along diagonal lines since it has to move horizontally as well as vertically to keep up with the spaceship. So the blue light beam traveled a greater distance in the same amount of time. That means that the blue light beam is actually traveling faster than the red one! But wait! Maxwell's equations said that the speed of light is constant, but it would appear that the speed of light can take different values in different reference frames!

You see, Galileo said that there is no such thing as absolute motion, and Maxwell's equations say that the speed of light is absolute. And in this way, the two theories were mutually exclusive. One or both of them had to be incorrect. But both theories had been verified experimentally to great levels of accuracy. What was the solution?

Einstein thought about this very carefully and realized that the two theories weren't quite mutually exclusive after all and the conundrum could be resolved – but only if a radical new assumption were made. Einstein realized that he would have to make time relative in the same way that Galileo made motion relative. Just as an object's speed through space depends on your point of view, an object's speed through time also depends on your point of view.

Let's go back to our example with the light clocks, but this time let's force light to have a constant speed, just like Maxwell's equations say. Now we see that if the beams travel at the same speed, then the blue light clock will tick more slowly than the red light clock. Or in other words, if we were riding on the red spaceship, we would measure the blue spaceship's clock as ticking more slowly. And this means that the red spaceship would measure time passing more slowly on the blue spaceship. But if we were riding on the blue spaceship, the opposite would be true. We would perceive the red spaceship's clock ticking more slowly, and thus we would measure its time passing more slowly.

So if the red spaceship thinks that the blue one's clock is ticking slowly, and the blue spaceship thinks that the red one's clock is ticking slowly, which one's correct? Which clock is actually ticking slowly? Well, it turns out this question would be just as meaningless as asking which spaceship is actually moving – it just depends on your reference frame. The blue spaceship's time is slow relative to the red spaceship, and the red spaceship's time is slow relative to the blue spaceship. This amazing fact is called time dilation. Time dilation sets the groundwork for Einstein's theory of special relativity.

Now let's take a moment to dispel a few myths about special relativity and hopefully make it a little bit clearer. First of all, remember that we only experience time changing for someone else, not for ourselves. So if you went near the speed of light, you wouldn't see your wrist watch start ticking slowly and you wouldn't see things moving in slow motion. Everything would be perfectly normal for you. We only experience time dilation occurring to other reference frames – that is, things that are moving relative to us.

Also, remember that if you hop on your bicycle and ride really fast, you won't notice any relativistic effects. But they're still there. They're just so minuscule that they're effectively impossible to detect. You have to go near the speed of light to experience time dilation and currently, even the fastest jet planes only go around seven millionths of the speed of light so they certainly don't experience any significant time dilation either.

Now, let's move on, because there are a few more amazing features of special relativity for us to discuss. One very important consequence of special relativity is the fact that light is the fastest thing in the universe. The reason for this is that if something went faster than light, it would actually go backwards in time, resulting in causal loops and other paradoxes. Now, that means that the speed of light is a sort of cosmic speed limit. All things with mass must travel slower than the speed of light. It can get really close to the speed of light, but as it approaches it becomes harder and harder to accelerate, so it will never quite get there. Furthermore, if you watch an object approaching the speed of light, you will actually measure it gain mass!

Now to understand this, let's talk for a minute about mass. What is mass? How do physicists define mass? Well often times, physicists use experimental definitions, meaning that the definition of a quality is based on an experiment that that you can perform to measure that quality. So how do you measure mass? Well the most obvious way would be to put an object on a scale. But in this case, you aren't actually measuring the mass – you're measuring the force of gravity acting on the object. And then, knowing the force of gravity, you can deduce how massive the object is.

But In the case of our spaceships in outer space that method wouldn't be very practical seeing as the force of gravity is so very weak. After all, you can't weigh something if it's weightless. So now how do you know how massive something is? Well, it's actually quite simple. All you have to do is apply a force to the object and see how much it accelerates.

Imagine floating out in space next to two spheres, one solid and one hollow. If you push equally hard on both spheres, the hollow one will accelerate a lot more than the solid one. In this way, you can tell which one is more massive.

The exact relationship between force, mass, and acceleration is represented by the equation $F = ma$. It says that the force you apply is equal to the mass of the object times the amount that it accelerates. Solving for mass, because that's the value we're interested in, we find that it's equal to the force divided by the acceleration.

Now imagine that you're in outer space, watching the spaceship accelerating. It turns on its thrusters, which provide a force, accelerating the spaceship. If you measure the force applied to the spaceship, and measure how much it accelerates, you can deduce how massive it is!

Well, let's imagine that the spaceship tries to accelerate to the speed of light. We observe that a force was applied, but the spaceship can't reach the speed of light, because that's the cosmic speed limit. Even though a lot of force was applied, it doesn't accelerate very much, and thus we calculate the mass to have increased! It's as if an object becomes more massive the faster it goes!

So if our two spaceships pass each other near the speed of light, then relative to the red spaceship, the blue one's mass will appear to have increased. And relative to the blue spaceship, the same will be true of the red spaceship. There is a sort of conversion between the energy that it takes to accelerate an object and the mass of that object. Einstein developed an equation related to this phenomenon: $E = mc^2$! $E = mc^2$ says that the energy in an object is equal to the mass of the object times the speed of light squared. So what does this mean?

$E = mc^2$ is telling us that all of the massive stuff in the universe (like stars, planets, spaceships – everything) is made of a sort of energy that's been frozen into substance, and that substance is what we call mass. Now it turns out that there's a huge amount of energy in a given amount of mass, because the conversion factor is the speed of light squared, which is ninety quadrillion m^2/sec^2.

Nuclear reactors take advantage of this enormous store of energy by releasing some of the energy that's trapped within atomic nuclei, resulting in vast amounts of power. This is a perfect example of how $E = mc^2$ had manifested itself in useful technologies.

But more than just being useful, $E = mc^2$ is also very elegant. It relates two of the most fundamental properties of existence, energy and matter, and demonstrates that they're simply different facets of the same thing. In fact, special relativity at large is very poetic. It shows us that light is like a constant standard to which all other things must compare. It transforms our understanding of time. And perhaps most profoundly, it reminds us that our observations can be misleading.

The goal of physics is to take us past our initial perceptions to identify the most plausible models of reality. The works of Albert Einstein are a powerful reminder that we must base their theories on carefully defined, measurable quantities because reality is seldom what it appears.