Concept: The Meaning of Relativity

Print

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Earlier in this course, we asserted that everything moves (See: "Concept: What Is Motion?" from Week 1). But even now, you're surrounded by contradictions to this statement. As you sit reading this essay, your desk isn't moving, your room isn't moving, the tree in your yard isn't moving. Or are they? It's all relative.

Today, we associate Einstein with the term "relativity." But the concept dates much farther back; and as with all scientific revolutions, everyone thought they understood what the word meant until the new model came along and took everyone by surprise. Einstein proposed that new model for relativity not once, but twice! In this essay we'll discuss the original (and still valid) meaning of the word—what we might call "Galilean relativity"—and Einstein's first, remarkable extension of that concept to a special case, called "special relativity." Next week, we'll talk about Einstein's second, even more amazing work on the subject—what we know today as "general relativity."

What Relativity Used to Mean (and Still Does, Usually)

Galileo Galilei pioneered the idea of relativity in the 17th century. Of course, people had thought before about moving objects and their speeds, and had seen how moving objects interact; but Galileo was the first to combine experiments, observations, and rigorous mathematical reasoning with abstract philosophical reasoning.

Although he didn't use the words, Galileo articulated the idea of the inertial frame of reference—a viewpoint that moved only in a straight line, without speeding up or slowing down. Let's say that you're in a boat on a lake, coasting eastward at five miles per hour. If I'm coming toward you in another boat, coasting westward at five miles per hour, then our relative speed is (5 + 5 =) 10 miles per hour. This seems to be just common sense; but Galileo asked, Who's moving compared to what reference? If we couldn't see the shoreline—a common reference frame for both of us—then we wouldn't be able to tell if you're floating still on the water and I'm going by you at 10 mph westward, or if I'm still and you're going by me at 10 mph eastward, or if we are each going five mph in opposite directions. Heck, it might even be the case that I'm traveling 30 mph westward, and you're traveling 20 mph westward—so that I'm catching up to you at 10 mph. Which situation is it, and how can we tell? Galileo realized that, since each boat is an inertial frame of reference, it doesn't matter. All that counts is our relative speed. Unless there's some sort of outside influence that can give us a clue—the shoreline, or the wind in our face, or a third boat that we can use as a marker—you simply can't tell.

Isaac Newton expanded Galileo's ideas of relativity, coined the word "inertia," and incorporated them into his laws of motion. As far as the laws of physics are concerned, Newton explained, the relative motion of two objects is what matters; and this kind of relativity had an "invariance"—a mathematical expression that shows how the objects' relative positions change as a result of their motion. Just add the velocities, and you're good to go. We call this property of moving bodies the "Galilean invariance." This is usually how relativity appears in our everyday lives. It's nothing special.

What Relativity Meant to Einstein in 1905

Galileo and Newton had no idea that their relativity didn't work for very fast motion. Why would they? The fastest vehicles of their time were ships in a good wind—maybe 40 miles per hour—and the fastest projectiles they knew of were probably cannonballs that traveled a few hundred miles per hour. Galilean invariance thus remained unchallenged until the serious study of light became possible in the laboratories of the late 1800s. The interferometric work of Michelson and Morley showed that the relativity of adding speeds—in this case,the speed of light with the speed of Earth's motion—wasn't working. What was wrong?

One interpretation of their results was put forth by the Irish physicist George Fitzgerald (1851-1901), and independently soon after by Lorentz, who along with fellow Dutch physicist Pieter Zeeman (1865-1943) received the second-ever Nobel Prize in Physics in 1902. They proposed that the length of any object changes when it moves—the faster it goes, the shorter it gets (referred to as Lorentz, or length, contraction). By 1899, Fitzgerald, Lorentz, and Larmor had written down and published versions of what we call today the "Lorentz transformations," which describe the mathematical expression of this motion-induced shrinkage.

Let's think about this length contraction idea for a moment. Imagine I'm riding in an ultra-high-speed train; in the lengthwise direction, the train shrinks from 100 feet long to 99 feet while I'm moving. That also means everything in the train shrinks by the same amount: the chair I'm sitting in shrinks from two feet long to 1.98 feet long, and the front-to-back length of my body shrinks from 11 inches to 10.89 inches. Then, everything returns to their normal dimensions when the train pulls to a stop at the station. It sounds ludicrous—but that's exactly what the Michelson and Morley experiment showed would happen. Again, though, the question remained: why did this effect happen?

Einstein's first paper on the subject, which was published in 1905, gave the reason. In its introduction he wrote, "according to the view to be developed here, neither will a space in absolute rest endowed with special properties be introduced, nor will a velocity vector be associated with a point of empty space…" underscoring again the critical notion that everything is relative, and nothing is absolute, when it comes to motion in the universe. But unlike Galileo, he would add a twist.

Special Relativity: The Basics

Einstein reaffirmed in his 1905 paper that the laws of physics don't change from one inertial reference frame to another. (Remember, an inertial frame of reference is something moving in a straight line at a constant speed.) If, for example, you're on a boat moving at 10 mph and throw a ball forward at 20 mph, an observer on the shore would see the ball moving at (10 + 20 =) 30 mph, while you would see the ball moving at just 20 mph. The laws of physics wouldn't change whether you're on the boat or on the shore; any motion detector on the boat would see the ball moving at 20 mph, and any motion detector on shore would see the ball moving at 30 mph.

Here's what makes Einstein's idea of relativity so unusual. Einstein explained that the universe has one glaring exception to the rule of relativity: the speed of light is constant, no matter what frame of reference you're in. So, if you're on that same boat, going 10 mph, and turn on a flashlight pointing forward, you see the flashlight beam traveling at the speed of light—and so does the observer on shore. That person does NOT see the light moving at (10 + the speed of light) mph. But the laws of physics must work the same way on shore as they do on the boat—so consequences result that seem very strange to those accustomed to seeing only Galilean relativity. One such consequence, proved Einstein, is shrinkage of length—the Lorentz contraction. So Einstein had created a model that explained the observation that light is constant in all directions.

How fast is the ball moving? It depends on your frame of reference. The person on the boat measures the speed of the ball at 10 mph. The person on shore measures the speed of the ball at 30 mph. ©AMNH

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How fast is light (c) moving? It is the same for any frame of reference. ©AMNH

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Since this new relativity mattered only for the special case of relative motion, namely for objects moving at constant speed with respect to one another, this model became known as the “Special Theory of Relativity.” Interestingly, Einstein noted in correspondence to a friend that he didn’t think this idea was all that special; rather, he thought it was a logical extension to the work already done by Lorentz and Fitzgerald. (At the time, Einstein was much more excited about the radical nature of his ideas regarding the photoelectric effect—a topic we’ll get to later in the course.)

So Einstein told us that the speed of a light beam is the same for any observer. So what? Well, it means that you’re aging at a different rate than I am—not because you eat more healthily and exercise more regularly, but because I’m walking down the street and you’re sitting at your computer. It also means that subatomic particles live longer than they should when they strike Earth from space, and that you could stay young compared to the rest of us—but also briefly put on a lot of weight—just by going really, really fast.

Special Relativity: Everyday Time Travel

When Einstein showed that time is a dimension like length, width, and height, he showed as well that we are always traveling through space-time. (More on the idea of "space-time" next week.) In this four-dimensional motion, if we move faster through space, then we move slower through time; if we move slower through space, then we move faster through time. So if you're moving faster than I am—walking, driving a car, or riding in the space shuttle—you're aging more slowly. This effect of moving clocks running more slowly is called time dilation.

The effect, however, is just about unnoticeable in ordinary life. A commercial jet liner cruises at a speed of about 300 meters per second; if you take the five-hour flight from New York to San Francisco at that speed, you will have traveled more slowly through time than I have. But 300 meters per second is still only one-millionth the speed of light; and you'll have gained a little less than 1/100,000,000 of a second on me. (Considering the airplane food you've just endured, I may well have come out ahead.) If you want to age appreciably more slowly, just go faster; if you travel 260,000 kilometers per second, for example—87% the speed of light—you'll experience time at half the rate I will; so if I perceive your round-trip to take one hour, you will have aged only 30 minutes.

The only obstacle to this miraculous anti-aging strategy? This speed is over thousands of times faster than any vehicle we've ever invented.

If you're skeptical of this result, let me assure you that time dilation has been confirmed experimentally. In 1972, scientists flew two atomic clocks on airplanes—one eastward, one westward, for many hours—and kept a third, identical clock stationary on the ground. After the planes landed, the clocks were examined—and sure enough, the clocks that had been airborne were off from the stationary one. The total effect was less than a millionth of a second, but the measurement was unambiguous and demonstrated the correctness of Einstein's relativity theory.

Special Relativity: Dilations, Contractions, and Gaining Mass

In Einstein's formulation of Special Relativity, a slower ride through time must be compensated by a faster ride through space. That means that from the perspective of a moving person, space must shrink in the direction of motion. To a person watching the motion go by, that effect manifests itself not as shrinkage of space, but of the person in motion. That's what we've been calling the Lorentz contraction.

There's one other quantity that changes as your speed increases: your mass increases too, inversely proportional to your time dilation and your Lorentz contraction. So while you're moving at 87% the speed of light, you may be aging at half the usual rate and you may be half your usual length, but you're also twice your usual mass. The closer you get to light speed, the more massive you get. Your length reduction and mass gain aren't permanent; you return to your usual mass when you stop moving. Your slower time travel, though, lasts forever.

Today, nuclear physicists rely on the mass gain feature of special relativity to conduct their experiments. They accelerate subatomic particles to nearly the speed of light to produce super-massive particles; then they crash them together. The byproducts of those extra-energetic collisions help to reveal the very nature of matter in the universe. These experiments would be completely impossible unless mass increases with speed; so the fact that particle accelerators and colliders work at all may be the best, most solid proof of Einstein's remarkable insight—the special theory of relativity.

Engineers fine-tune the Brookhaven Relativistic Heavy Ion Collider. Two rings of powerful superconducting magnets guide particles in opposite directions, culminating in collisions that explain the nature of matter. ©Brookhaven National Laboratory

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Related Links

Think Like Einstein

Read a short PBS tutorial that covers the basics of Einstein's Special Theory of Relativity.

Clocks Moving Slower Animation

This animation, produced for the Einstein exhibition by the American Museum of Natural History, uses light clocks to show how time slows for objects in motion.

C-Ship: The Lorentz Contraction

Here is a technical summary on the Lorentz Contraction, using animations of a spaceship traveling through space.

C-Ship: Time Dilation

Study a technical summary on time dilation.