Einstein's Theory of Special Relativity

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1 Author's Note

Einstein's Special Theory of Relativity was a breakthrough in classical physics, opening an entirely new way of thinking about the universe. In a high school physics class it is uncommon to learn about Einstein's theories of relativity because they are complicated. Instead we learn about Newtonian Mechanics (physics discovered by Isaac Newton) because it is good enough to interpret the world we live in today, I mean, heck, it brought us to the moon. We learn about Newtonian physics because it makes sense, it accurately describes motion at relatively slow velocities, but becomes unreliable at high velocities which is where Einstein comes in.

2 Introduction

Einstein championed two theories of relativity, General Theory of Relativity (General Relativity) and Special Theory of Relativity (Special Relativity). Special Relativity, published in 1905, comes before General Relativity, published in 1915. Special Relativity talks about relative motion at a constant velocity, in other words, an object that is moving at a constant "speed" being observed, like a car moving towards/away from you. Its significance is that it showed time, space, and even mass aren't fixed but depend on how fast something is moving, which completely changed our understanding of the universe.

3 Einstein's Two Postulates

When developing his Theory, Einstein makes two assumptions, he postulates:

1. **Galilean Relativity.** A theory formulated by Galileo Galilei in the 17th century, exists which states there isn't a preferred or an absolute frame of reference. Now you might be asking, "what is a frame of reference?" To answer that question simply, a frame of reference is the perspective from which motion, position, and time are measured. For example, a person standing on the sidewalk watching a car pass and a person sitting inside that moving car are in different frames of reference. Einstein is

using Galileo's theory to say neither frame is preferred and motion is always relative, the person in the car can say, "why is the person on the sidewalk moving past me", and the person on the sidewalk can say, "why is the person in the car moving past me", and technically neither would be wrong because no frame or judgment of motion is preferred.

2. **The Speed of Light is Constant.** Light has a speed limit, and no matter how many times it is measured, it will always yield the same value.

Einstein then goes further to say, if we assume the speed of light is constant three things must be true:

1. **Length Contraction.** At high speeds, objects contract in the direction of motion. A spaceship moving at 99.99% the speed of light appears shorter to a stationary observer.

2. **Time Dilation.** At high speeds, time passes more slowly. A clock on a spaceship moving at 99.99% the speed of light would tick more slowly, and to a stationary observer, people inside the spaceship would appear to move in slow motion.

3. **Relativistic Mass Increase.** At high speeds, an object's measured mass increases. A spaceship moving at 99.99% the speed of light would be measured as having greater mass by a stationary observer.

4 Gamma (γ): The Number Behind Relativity

The beauty of Special Relativity is that Einstein's derivations of the theory involved algebra, allowing the reasoning of the theory to be obtained without the use of calculus. Starting from two fundamental postulates (shown in the previous section), Einstein derived the equations of special relativity using the Lorentz transformations, a set of equations that included the time dimension (t) on top of the already established spatial dimensions (x, y, z).

The ripe juice of special relativity has to do with a value he derived from the Lorentz transformations, γ. If you read Einstein's publication on special relativity you will encounter a lot of complex nomenclature but this value is most relevant to the theory and intuitive to understand. γ is defined as $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

It seems frightening, but it is not scary at all. Gamma defines the experience of relativistic effects: length contraction, time dilation, and relativistic mass increase. With c being the speed of light (defined as a constant) and v being velocity, gamma is a function with respect to velocity, f(v). As velocity increases, these relativistic effects become stronger. A spaceship moving at 99.99% the speed of light would experience stronger relativistic effects than one moving at 99.98% the speed of light (refer back to the previous section). Gamma increases asymptotically as velocity approaches the speed of light, so objects with high gamma values exhibit all three effects more strongly.

So yes, a human that is on a plane would technically experience relativistic effects. However, there gamma value would be so close to 1 that the effects would be unnoticeable. Time dilation, mass dilation, and length contraction become significant only when there is a large deviation of gamma from one.

The equation for length contraction is $L = \frac{L_0}{\gamma}$, where L_0 (L naught) is the proper length measured in the object's rest frame, and L is the length measured by an observer moving relative to the object. From our frame, a higher *gamma* means the object appears shorter along the direction of motion.

The equation for time dilation is $t = \gamma * t_0$, where t_0 (t naught) is the proper time measured in the rest frame of the moving clock, and $t$is the time measured by an observer in a different frame. From our frame, a higher *gamma* means the moving clock runs slower, so the time interval appears longer.

The equation for relativistic mass is $m = \gamma * m_0$, where m_0 (m naught) is the rest mass measured in the object's rest frame, and m is the mass measured by an observer in a different frame. From our frame, a higher *gamma* means the object appears more massive and because the volume of the object is not increased, in fact length contraction tells us it's decreasing, the object therefore becomes more dense.

To contextualize it a bit further, let us go back to the plane example and say that it is traveling at 200 m/s, if we plug that into our velocity, and the speed of light is $= 3 * 10^8$ m/s, $\gamma = \frac{1}{\sqrt{1 - \frac{(250m/s)^2}{(3x10^8 m/s)^2}}} = 1.000000000000347$

A value that defines the most likely max relativistic effects in our lifetime, unnoticeable yet present.

5 The Most Famous Result of Relativity

So far special relativity threw classical physicists in the early 20th century into a frenzy, but there's more. Buried within Einstein's equations is a result so profound that it reshaped physics entirely. Beyond mass dilation, there is a deeper consequence hidden in Einstein's equations: the famous equation $E = mc^2$. This shows that mass and energy are two forms of the same thing. All energy changes manifest in a change in mass. This connects directly to what we just discussed. As an object's velocity increases, its relativistic mass increases, which means it effectively stores more energy. Gamma not only affects length, time, and mass, it also links an object's motion to its total energy, showing how energy and mass are fundamentally interchangeable.

6 Why Special Relativity Matters?

Special relativity matters because it completely changed how we understand space, time, and motion. Before Einstein, physics assumed that time and space were fixed and universal, but his theory showed that these quantities depend on the observer's motion. Through the concept of gamma, we can see how motion at high speeds affects length, time, and mass, and even everyday objects like a plane are technically subject to these effects, even if the changes are too small to notice. Beyond these relativistic effects, special relativity revealed the deep connection between mass and energy with the equation $E = mc^2$, showing that energy and mass are interchangeable and fundamentally linked. This insight reshaped modern physics, influencing everything from particle physics to cosmology, and it provides the foundation for technologies like GPS, which must account for time dilation to work accurately. Special relativity matters because it allows us to understand the universe in a more complete, precise, and unified way.