How Special Relativity Works

by Wayne D. Smith, PhD, SFSPE

Special relativity theory has two main principles, both enunciated by the German physicist Albert Einstein in 1905. The first principle does away with the concept of absolute space. The other does away with the concept of absolute time. Further, Einstein rejected the idea of an ether as an absolute frame of reference for space. Then, he conceived a mathematical theory that resolved the problem of measuring the speed of light as being the same regardless of when and how it is observed.

The Theory[1]

Special relativity theory led to history's most famous equation, $E = mc^2$, where E represents energy, m represents mass, and c represents the speed of light. The first principle of special relativity is that the basic laws of physics are the same everywhere and for all observers, regardless of where the observers are or how fast they might be moving.

The second principle of special relativity is that there exists a fourth dimension: *time*. An object's position can be generally described by three dimensions of space: either right or left, either up or down, and either in or out. Three dimensions are sufficient to describe where any object is located in space. However, a fourth dimension of *time* is needed to describe when (either past or future) an object exists in that space. By coupling time with the three dimensions of space, Einstein was able to reconcile long-standing inconsistencies regarding Newton's ideas about nature. He was also able to explain the results of the Michelson-Morley experiment.

Einstein postulated that the numerical value of the speed of light is an absolutely constant number at all times and to all observers, regardless of when, where or how light is measured. In fact, issues of space and time are so intertwined in Einstein's view of the universe that he urged scientists to regard these two quantities not as space and time, but as one *spacetime.*

Spacetime[2]

The concept of spacetime is not particularly difficult to understand. We regularly encounter spacetime notions throughout our lives, often without recognizing them. When arranging to meet someone, we must specify not only the place to meet, but also the time. Otherwise, we would never rendezvous successfully in order to create the event of meeting at the same place and at the same time.

The two, space and time, are intimately coupled. Looking out in space is looking back in time. This is why astronomers contend that looking through their telescopes is equivalent to probing back into time. Telescopes are time machines, and astronomers are historians. Together, they probe the past. Relativity permits movement into the future at rates faster than those allowed by common sense.

But events cannot, under any circumstance, transpire toward the past. Travel into the past would violate a basic principle of cause and effect. The cause of an event must precede the effect of that event. So we can never travel backwards in time. Otherwise, impossible events would occur. For example, we could potentially experience our existence prior to the birth of our parents, which is absurd.

Voyages into the past violate not only the philosophy of cause and effect, but also the central dogma of biology as well. We can observe the past by looking outward into space, but the laws of physics absolutely prohibit journeys into the past. Travel into the future, however, is not prohibited by cause-and-effect arguments.

The Speed Limit[3]

Most physicists maintain that no object of any type can travel faster than the speed of light. Contrary to popular belief, however, this is not a direct conclusion of special relativity theory. Some theorists have stressed that Einstein's ideas in no way prohibit the existence of faster-than-light objects. Researchers have recently proposed three general classes of physical objects. The first class comprises relatively slow-moving objects, such as atoms and molecules.

All scientists agree that atoms and molecules exist. Furthermore, all agree that relativity predicts weird observational consequences whenever any of these objects travel close to the speed of light. All researchers agree that these often sluggish objects cannot be accelerated beyond the speed of light barrier. But a second class of objects, exclusively subatomic particles, move at the speed of light.

For example, scientists have never detected photons or neutrinos traveling at more or less than the speed of light. Instead, they are instantaneously created in nuclear reactions, after which they immediately zip away at the speed of light. Nor do they slow down or speed up. Can special relativity accommodate a third class of objects that move with speeds faster than that of light?

The mathematical answer seems to be that they could exist, provided they never attempted to slow down. In other words, these particles would also find the speed of light to be a limiting value or barrier. They could not travel slower than the speed of light. Such particles are called *tachyons.*

Currently, physicists have no evidence for the existence of tachyons, despite much experimental effort to detect them. Theoretically, though, nothing in relativity theory seems to exclude them. What relativity does clearly prohibit is crossing the speed of light barrier. Accordingly, no object in our everyday world could travel faster than light, whereas no tachyon could travel slower.

Light Speed[4]

The speed of light is constant, no matter what your frame of reference. Consider two cars that are traveling in opposite directions and approaching one another. Common sense, and Newtonian theory, predict that the relative speed is the sum of the individual speeds of the cars. For example, if one is traveling at 40 miles an hour and the other one is traveling at 60 miles an hour, then the relative speed is the sum of the two speeds, or 100 miles an hour. This is nothing more than common sense gained from everyday experience with moving objects.

Descriptions of all motions, analyzed by the laws of Newton, derive from hardly more than human intuition. Reasoning of this type is completely valid in our everyday world in realms of speeds much slower than light. But when particles move toward or away from one another with a speed close to or equal to the speed of light (as does radiation), then Newtonian physics no longer gives a correct description of reality.

The Michelson-Morley experiment in the nineteenth century, and numerous experiments since, have clearly demonstrated that no matter can exceed the speed of light. While Newtonian reasoning seems to work properly for small speeds, it fails for very high speeds. Fortunately, Einstein was able to figure things out.

Einstein showed that the correct relative speed of two very fast moving objects is derived from a detailed mathematical analysis of the nature of space and time. An aspect of this factor appears throughout the theory of special relativity, affecting almost all physical quantities. It is the factor that alters our commonsense notions of natural phenomena.

Time and Length[5]

The relativistic factor inundated the theory of relativity. It is attached to virtually every physical quantity describing an object or an event within our four-dimensional universe. Accordingly, an object behaves as expected on the basis of common sense only if its speed is small compared with that of light. But once the relativistic factor begins to depart from us as the speed of any object approaches that of light, some demonstrably weird effects can occur.

Imagine a spaceship traveling past us with a speed typical of those man-made craft now exploring the Solar System. While the spaceship passes rather slowly by us, our estimates of the ship's physical quantities would match the values measured by the travelers on-board the spacecraft. Everyone would agree and commonsense would prevail. But, if the spaceship were to pass us with a speed close to the speed of light, the relativistic factor would affect the outcomes of our observations.

For one thing, if we could see a clock on-board a rapidly moving spaceship, we would measure the clock to be ticking more slowly than normal. This effect, called time dilation, has nothing to do with the construction of the clock, because it applies equally to biological rhythms (such as heart beats). Nor are the mechanical workings of the clock affected by motion. The on-board travelers experience no strange timing problems. Put simply, the measurements of time depend on the relative speed between the observers.

Similarly, our estimate of the spacecraft's length would no longer agree with those measured by the on-board travelers or by us when the spaceship passed more slowly. Instead, we as observers would measure a smaller spaceship. Its length would have shrunk. The greater the spaceship's speed , the greater the amount of shrinkage. Just as with time dilation, this length contraction effect is not an optical illusion.

Nor should we try to find a mechanical cause for the shortening. It is the spacecraft's speed alone that causes the ship to be shortened in the direction of its motion. It is not an overall shrinkage of the entire spacecraft's size, but only a shortening of the craft in the direction of its motion. Should the spaceship attain the speed of light itself, it would diminish to nothing at all.

The travelers share the same frame of reference as the on-board meter sticks, as well as the same frame of reference of the spaceship itself. There is no relative motion between the on-board travelers and their spacecraft, or between the on-board travelers and their on-board meter sticks. Thus, the travelers deduce a relativistic factor of unity, provided they examine objects within the spaceship.

But once they look out of the ship's window, their perspective changes. Now they see their motion relative to the outside world and deduce a different relativistic factor. In other words, as the on-board travelers peer through the spaceship's windows at us, we all look smaller. The space travelers see us as thinner individuals. If we are holding a meter stick horizontally, they will measure it to be less than a meter.

But which objects (or people) are really shortened, the ones on the spaceship or us? The answer is that both observers are correct. The bizarre consequences of relativity theory apply to any and all observers, provided they share some large relative speed. Measurements of length and time depend upon the frame of reference from which they are made. It's all a matter of relative speed, hence the name *relativity theory.*

Mass and Energy[6]

The relativistic factor also has an effect on mass. If the spacecraft were moving close to the speed of light relative to us, we would measure its mass to be greater than when it was at rest. In principle, we could set up an experiment and physically measure the spaceship's mass to have increased. The greater the ship's speed relative to us, the larger the additional mass measured by us.

Even the travelers on board become more massive from our viewpoint. But like length, the physical mass is unchanged from the perspective of the travelers on-board the spacecraft. They do not measure their rapidly moving ship to be more massive than usual, and they also appear to be normal.

That is because, relative to the spaceship, their speed is zero and their relativistic factor is one. They are correct in viewing their spaceship as normal, but we are also correct in viewing it as grossly overweight. Measurements of mass, like those of length, depend on the relative speed of the frame of reference from which they are measured.

When an object moves at a high speed, the increase in its *mass* comes from its *energy.* It is on this basis that Einstein arrived at a conclusion of immense importance to the world. He reasoned that since the mass of a moving body increases as its motion increases, and since motion is a form of kinetic energy, then the increased mass of a moving body must result from its increased energy. In short, energy must have some mass, and in a few mathematical manipulations he proved that $E = mc^2$.

Conclusion

The relativistic factor was introduced by Einstein to account for repeated observations that showed that the speed of light in a vacuum is constant and that there is no ether, no absolute frame of reference. Due to the relativistic factor, measurements of time, length and mass all depend on the relative speed between observers. The most astounding outcome of these effects is that matter and energy are interchangeable. This is special relativity theory in a nutshell.

NOTES

1. Lawrence Krauss, *Atom: An Odyssey from the Big Bang to Life on Earth* (New York, NY: Little, Brown, and Co., 2001).

2. Steven Weinberg, *To Explain the World: The Discovery of Modern Science* (New York, NY: Harper-Collins, 2015).

3. Paul Davies, *Cosmic Blueprint: New Discoveries in Nature's Ability to Order the Universe* (New York, NY: Templeton Foundation, 2004).

4. Martin Rees, *Just Six Numbers: The Deep Forces That Shape the Universe* (New York, NY: Basic Books, 1999).

5. Sean Carroll, *The Particle at the End of the Universe: The Hunt for the Higgs* (New York, NY: Penguin Books, 2012).

6. Lawrence Krauss, *The Greatest Story Ever Told - So Far: Why are We Here?* (New York, NY: Atria Books, 2017).