Lesson 12
Relativity

Introduction: Connecting Your Learning

Relative motion was studied at the beginning of the course when the simple notion of adding or subtracting velocities made perfect sense. If two automobiles approach each other head on going 50 mph, it is the same as one auto being at rest and the other going 100 mph. An observer standing at the side of the road would observe each auto going 50 mph in opposite directions. A person in one of the autos would measure the other auto going 100 mph. In most disciplines, ideas can be extended to include extreme cases (i.e., very large-very small, very fast-very slow, etc.), but that is not true in physics. When objects approach the speed of light, it becomes a new game, and the physics seems to change. In reality, however, the physics does not change. At everyday speeds, the rules of classical physics (i.e., Newton's Laws) work fine. When it comes to light rays traveling, the above rationale breaks down. The speed of light is completely independent of the motion of the observer, which is something people are not used to. This lesson illustrates that when objects travel at speeds near the speed of light, time slows down and length of the object gets smaller. Even though it sounds like science fiction, it is not. It has, however, been one of the significant revelations in twentieth and twenty-first century physics.

Readings, Resources, and Assignments	
Required Textbook Readings	None

Check Prior Knowledge

Check your prior knowledge by matching these terms.

Term	Definition
Inertial reference frame	Moving clocks run slower than when at rest
Ether	Measure of distance
Relativity Principle	The medium in which light was assumed to travel in
Time dilation	Gravitation mass is the same as inertial mass
Length contraction	3.26 Light-years
$E = mc^2$	The laws of physics are the same in all inertial reference frames
Light year	Not accelerating
Equivalence Principle	Moving objects are shorter (in the direction of motion) than the object is at rest.
Parsec	Mass and energy are related

Focusing Your Learning

Lesson Objectives

By the end of this lesson, you should be able to:

1. Discuss the Michelson-Morley experiment and its implications in terms of the Special Theory of Relativity.
2. Discuss the implications of the first and second postulates of the Special Theory of Relativity.
3. Discuss the concepts of time dilation and length contraction as related to the Special Theory of Relativity.
4. Discuss the equivalence of mass and energy as related to the Special Theory of Relativity.
5. Differentiate between an inertial and non-inertial frame of reference.
6. Differentiate between gravitational mass and inertial mass as it pertains to the General Theory of Relativity.
7. Compare and contrast the Correspondence Principle and the Principle of Equivalence as they apply to relativity.

Approaching the Objectives

This lesson is comprised of four sections:

Section 1: Special Theory of Relativity

Section 2: Twin Trip into Space

Section 3: General Theory of Relativity

Section 4: Gravity and Space

Section 1: Special Theory of Relativity

Many consequences of relativity are counter to everyday beliefs and common sense. You may not understand relativity the first time around, since humans tend to retain beliefs associated with common sense.

Special relativity is a subset of general relativity and is usually considered easier on the mind. Special relativity is restricted to objects moving in uniform relative motion (i.e., motion without acceleration). General relativity relaxes the constraint of no acceleration and considers any relative motion, including motion in an accelerated frame of reference.

Special relativity is grounded in two basic postulates. The first postulate states that the laws of physics are the same in all inertial reference frames. What exactly does that mean? The implication of the postulate is that if an experiment is performed and Newton's 2nd Law (F=ma) is used to calculate the results, then the same law of physics (F=ma) holds true in the same experiment performed by someone moving at constant speed relative to the first person. The first postulate is easy on the mind; it aligns well with common sense. The second postulate is a bit more incomprehensible. If a person is swimming in a river that has a current, the person moving with the current will be measured as going faster than the person trying to swim against the current (i.e., common sense). The second postulate of the Special Theory states that light will always propagate through a vacuum at a definite velocity, c, which is independent of the motion of the source or the observer. This notion definitely contradicts common sense observations in the everyday world.

The famous experiment performed by Michelson and Morley postulated that light is a wave and therefore, needs a medium in which to travel. The medium was named ether and can be visualized as the water flowing in a river. In the experiment, light (i.e., the swimmer) was emitted in different directions, and measurements were made to calculate the speed of the light. Since the distances were known and the time was accurately measured, the velocity was then calculated. Because swimmers would definitely have different times depending on their relative motion with the current, the scientists presumed light should behave the same way. They discovered that it made no difference whether the light was going “with the ether” or against it. This experiment, along with experiments being conducted by Einstein and others, showed that the ether was not necessary in order for light to propagate. This was a huge revelation in physics at the time. This categorizes light (and other forms of electromagnetic radiation) as a different kind of “wave.” The “wave” did not require a medium in which to travel, and furthermore, the relative motion of the observer making the measurements did not influence the speed of the “wave.”

Activity: Perform an Internet search to explore the Michelson-Morley experiment in more detail.

a. Make a sketch of the interferometer used and describe the basic operating fundamentals.

b. Discuss the evidence that Michelson and Morley were expecting to confirm the existence of the ether. Relate this to properties of light learned in previous lessons.

What is the concept related to the properties of light? Check your answer at the bottom of the lesson.

Further consequences are derived from this theory. Two events that occur simultaneously for one observer may not appear simultaneous to another observer.

Relativity can become rather mathematical in a hurry, so leaving some mathematics behind, it can be shown that when objects move at speeds near the speed of light, other counterintuitive phenomena occur.

Time is dilated. This means that moving clocks actually run slower than stationary clocks. This has been experimentally verified by time measurements in extremely fast airplanes.

Length in the direction of motion is contracted. This means that an object that is one meter long and moving at a speed near the speed of light will actually be shorter than the same object at rest. This obviously goes against common sense for most people. However, it is perfectly consistent with the rest of the Special Theory of Relativity.

The equations for time dilation and length contraction are given below.

$$\mathbf{t = t_o / ((1 - v^2/c^2)^{1/2})}$$

$$\mathbf{L = (1 - v^2/c^2)^{1/2} L_o}$$

Note: Raising to the ½ power is the same as taking the square root.

The ("o" subscript indicts the stationary measurement)

The "v" is the speed of the object.

The "c" is the speed of light

c is defined as 2.99792458×10^8 m/s

This is almost always rounded to 3×10^8 m/s

Also note in the above equation, if “v” "c” (i.e., everyday world), then the lengths and times are the same because v2/c2 approximates zero.

The classic “thought experiment” used in almost every modern physics class to illustrate the consequences of time dilation involves starting with twins (same age) and sending one into outer space (moving at speeds near the speed of light) and keeping the other twin on Earth. The next section may surprise the common sense of the reader.

Section 2: Twin Trip into Space

Perform an Internet search using search terms such as relativity games, special relativity, Einstein Nobel prize, or other related terms. There are several excellent Web sites with animated games illustrating the mathematically complicated theories of relativity in much simpler terms. Here is one example.

The twin trip into space is the classic example used in physics courses to illustrate how time is affected when an object travels at speeds near the speed of light. On first encounter, this may seem like science fiction; however actual clocks have been tested in extremely fast airplanes and time measurements have actually shown a difference in time between moving and stationary clocks. Note that measuring parameters and explaining why things occur as they do are entirely different matters!

The basic story involves two people who are the same age. One of the twins is sent into space (traveling near the speed of light) and the other remains on Earth. The twin blasted into space travels out for a set time and then turns around and returns to Earth. The story is considered a paradox, because special relativity implies that either twin can be considered at rest while the other twin is moving relative to the first. If there were two valid inertial reference frames, this would be true. Either twin could be considered at rest with respect to the other. However, there are actually three frames of reference. They are (1) the reference frame of the twin on Earth, (2) the reference frame of the twin moving from Earth into space, and (3) the reference frame of the twin moving from space back to Earth. The fact that the twin is the same person is not relevant; the reference frames for coming and going are different.

The twin that stays behind will not age as fast. The twin’s physiology and body clocks will run slower. Suppose the 10-year-old twins are named Michael and Shannon. Michael stays on Earth, and Shannon (the adventurous twin) climbs into the spaceship and zooms off at 99.99 percent the speed of light. The total trip takes 50 years to reach the destination in space and return. When Shannon gets back, Michael is 60 years old. Shannon, on the other hand, has not reached her eleventh birthday. Although it seems like science fiction, it is not! Shannon only lived about one-half year, while Michael aged 50 years. There are numerous Web sites on the Internet that explain this paradox using varying degrees of mathematics. Interested students should research this phenomenon and find an explanation that aligns with the level of mathematics in their comfort zone.

Einstein was famous for his “thought experiments.” These are experiments not actually performed such as the twin paradox above. The next section explores an extension of the Special Theory of Relativity, which includes the more general case of accelerated relative motion.

Section 3: General Theory of Relativity

Around 1950 Einstein formulated an extension to the Special Theory that took into account accelerated reference frames. Most people have little trouble thinking in three dimensions, because space takes up three dimensions. Many think of time as a separate dimension that only has one direction (i.e., forward or advancing). Furthermore, time is usually considered the independent variable upon which other variables (i.e., position, velocity, etc.) depend. Einstein changed all this when he combined the three dimensions of space with the dimension of time and regarded the combination as one entity. Some refer to this as the space-time continuum. It is difficult to visualize four dimensions in a three-dimensional world. Some attempts have depicted the space-time continuum as a flexible elastic piece of fabric, capable of stretching and becoming deformed. It is important to realize this is just a model to help people visualize and keep variables straight.

Einstein believed that a mass placed near the space-time continuum would cause the space -time “fabric” to become deformed. In essence, space-time curved in the presence of matter.

Mass is a term that describes the amount of matter in an object and the energy contained by that same object. Mass can be described as inertial mass. Large masses have more inertia than smaller masses, because it takes more force to accelerate them. Mass can also be described by the gravitational attraction of one object on another. This prompted the question that set the physics community scrambling to see if the two masses (i.e., gravitational and inertial) were identical. To date, no experiment has shown any difference between an object’s gravitational mass and its inertial mass. This has caused the physics community to search for a link between gravity and mass. Since the force of gravity is attractive, another force was sought after that would balance gravity and account for what physicists thought was a static universe. The force was never found; instead, one of the consequences of the General Theory of Relativity is that the universe must be expanding. The mathematics to show this is well beyond the scope of this course. The important point is that science is not a static collection of facts to memorize, but instead, a dynamic collection of theories that are constantly changing.

Activity: Think about your everyday life as a student, a sibling, a parent, or whatever category you may identify with. Develop the Special Theory of ______________ (you name it). Make sure that it either does or could pertain to you. You can make one up if you don't want to get personal. Develop at least two postulates that fit the theory.

Now extend the theory to encompass more detail and make the theory more general. Name this theory The General Theory of ________________. Provide at least one solid link between the two theories.

The final section extends the gravity-space concept and includes reading a recent article that discusses Einstein’s theories and applies the theory beyond the classroom.

Section 4: Gravity and Space

Read the article "Einstein Theory Applies Beyond the Solar System," by Kitta MacPherson, *Space Daily*, 3/15/10. Gale General OneFile Database. Respond to the following true/false questions and check your answers at the end of the lesson.

a. The General Theory of Relativity applies at cosmic scales as well as more local regions in space.

b. The General Theory of Relativity describes the interplay between gravity, space, time, and the history of cosmology.

c. Author Eddington proved Einstein's General Theory of Relativity.

d. Author Eddington observed starlight bending around the Sun, which was supported by The General Theory of Relativity.

e. Understanding the General Theory can help understand the origin of the universe and other basic forces in physics.

f. According to Einstein the flow of time is not affected by gravity.

g. To date there have been no theories proposed as alternatives to Einstein's theories.

h. Relativity requires that the curvature of space be equivalent to the curvature of time.

Summarizing Your Learning

This lesson explored the mysteries associated with a branch of physics not usually studied at the elementary college level. Hopefully, you learned to keep an open mind. Just because something does not fit into the predefined way of thinking, that in and of itself, should not preclude it from investigation. The twentieth century was a very exciting time for the physics community. Significant models of particles not seen with the naked eye (i.e., atoms and molecules) were developed. Light and other portions of the electromagnetic spectrum were linked with electricity and magnetism. Tremendous advances were made in space exploration. The twenty-first century presents new challenges that will require massive amounts of critical thought, experimentation, and plain hard work if societies expect to retain sustainability on Planet Earth. A solid foundation in physics is just the start!

Practice Answers

Check Prior Knowledge

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Inertial reference frame	Not accelerating
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$E = mc^2$	Mass and energy are related
Light year	Measure of distance
Equivalence Principle	Gravitation mass is the same as inertial mass
Parsec	3.26 Light-years

Section 1: Special Theory of Relativity

What is the concept related to the properties of light? Interference fringes

Section 4: Gravity and Space

a. The General Theory of Relativity applies at cosmic scales as well as more local regions in space. True

b. The General Theory of Relativity describes the interplay between gravity, space, time, and the history of cosmology. False. The history of cosmology is interesting, but not part of the General Theory.

c. Author Eddington proved Einstein's General Theory of Relativity. False. Trick question! The article said he did; however, physics students know that theories can never be proven correct, only incorrect!

d. Author Eddington observed starlight bending around the Sun, which was supported by The General Theory of Relativity. True

e. Understanding the General Theory can help understand the origin of the universe and other basic forces in physics. True.

f. According to Einstein, the flow of time is not affected by gravity. False. Just the opposite. Clocks located a distance from a large gravitational source will run faster than clocks located near the source.

g. To date there have been no theories proposed as alternatives to Einstein's theories. False. Some of the alternative theories eliminate the need for dark energy, which Einstein's theories require for the mathematics to work out.

h. Relativity requires that the curvature of space be equivalent to the curvature of time. True.