CP1 & honors (not AP®)

Speed of Light

Unit: Special Relativity

NGSS Standards/MA Curriculum Frameworks (2016): N/A

AP® Physics 1 Learning Objectives/Essential Knowledge (2024): 1.D.3.1

Mastery Objective(s): (Students will be able to…)

- Understand that the speed of light is constant in all reference frames.

Success Criteria:

- Explanations account for observed behavior.

Language Objectives:

- Explain why scientists hesitated to accept the idea that the speed of light does not depend on the reference frame.

Tier 2 Vocabulary: reference frame

Notes:

Prior to the late 17th century, it was thought that light traveled instantaneously. In 1676, Danish astronomer Ole Rømer was the first to demonstrate that light traveled at a measurable speed.

The context for Rømer's discovery begins with the invention of the telescope in in the Netherlands in 1608. Two years later, in 1610, Italian astronomer Galileo Galilei discovered the four largest moons of Jupiter. In 1616–1617, Galileo proposed that the timing of the eclipses of Jupiter's moons (by Jupiter) could be used as a cosmic clock to calculate longitude. (Mechanical clocks of the time were not precise enough to do this.) These measurements were first made successfully about 50 years later by Italian-French astronomer Giovanni Cassini. Rømer met Cassini at the Royal Observatory in Paris where the two worked together.

Rømer observed that the time between the eclipses of Jupiter's moons varied slightly over the course of a year. Through Kepler's laws, Rømer knew the orbital paths of the Earth and Jupiter, and was able to calculate the distance between them at different times of the year. Rømer discovered that the time interval between eclipses decreased when the Earth and Jupiter were moving toward each other, and increased when they were moving away from each other. He reasoned that the time discrepancies could be explained by the assumption that light moves at a constant, measurable speed.

Rømer's calculated valued of the speed of light was about 24% slower than the currently accepted value of $2.998\times10^{8}\,\frac{\text{m}}{\text{s}}$. Rømer's theory was controversial, but was accepted by Isaac Newton and by Dutch mathematician, physicist, engineer, astronomer, and inventor Christiaan Huygens, and was finally confirmed by English astronomer James Bradley in 1729, about 20 years after Rømer's death.

Principle of Relativity

The principle of relativity was first explicitly stated by Galileo Galilei in 1632 in his *Dialogue Concerning the Two Chief World Systems*. The principle of relativity states that ***the equations that describe the laws of physics are the same in all frames of reference***.

If this principle is true, it must be true for measurements and reference frames involving light.

In 1864, based on the principle of relativity, physicist James Clerk Maxwell united four calculus equations involving magnetic and electric fields into one unified theory of light. The four equations are:

1. Gauss's Law (which describes the relationship between an electric field and the electric charges that cause it).
2. Gauss's Law for Magnetism (which states that there are no discrete North and South magnetic charges).
3. Faraday's Law (which describes how a changing magnetic field creates an electric field).
4. Ampère's Law (which describes how an electric current can create a magnetic field), including Maxwell's own correction (which describes how a changing electric field can also create a magnetic field).

According to Maxwell's theory, light travels as an electromagnetic wave, *i.e.,* a wave of both electrical and magnetic energy. The moving electric field produces a magnetic field, and the moving magnetic field produces an electric field. Thus, the electric and magnetic fields of the electromagnetic wave reinforce each other and propagate each other through space.

CP1 & honors (not AP®)

From Maxwell's equations, starting from the measured values for two physical constants: the electric permittivity of free space (ε_o) and the magnetic permeability of a vacuum (μ_o), Maxwell determined that the speed of light in a vacuum must be:

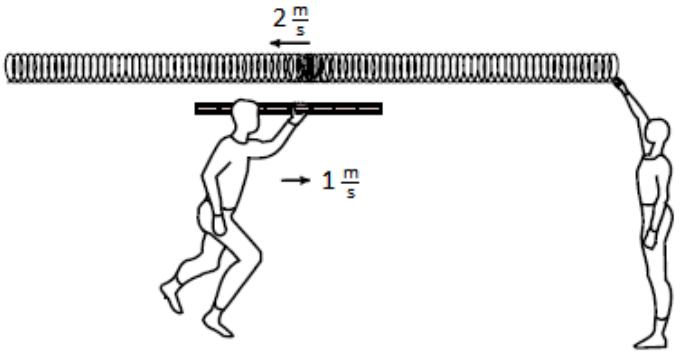
$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} = 2.997\,924\,58 \times 10^8 \ \tfrac{\text{m}}{\text{s}}\ ^*$$

Both μ_o and ε_0 are physical constants, which do not depend on the reference frame. Maxwell theorized that the speed of light in a vacuum must therefore also be a physical constant, and it therefore cannot depend on the reference frame that is used to measure it.

This means:

1. Light travels at a constant velocity, regardless of whether the light is produced by something that is moving or stationary.
2. The velocity of light is the same in all reference frames. This means a photon of light moves at the same velocity, regardless of whether that velocity is measured by an observer who is stationary or by an observer who is moving.

Recall from *Relative Motion* starting on page 213, that the relative velocity of two objects is the vector sum of their individual velocities:

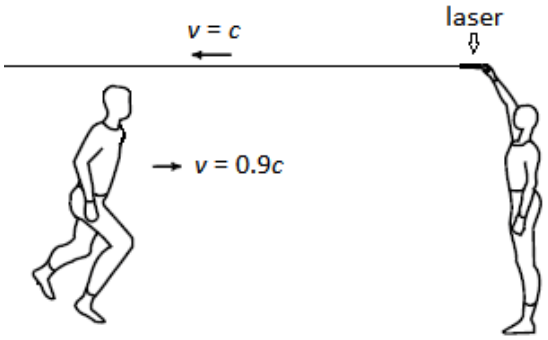


In this case, in the reference frame of the runner, the wave is approaching at a velocity of $3\frac{\text{m}}{\text{s}}$.

* This is an exact value as defined by the International Committee for Weights and Measures in 2019 and is one of the seven Defining Constants used to determine exact values of other constants in the International System of Units (SI).

CP1 & honors (not AP®)

However, if the wave in the above relative velocity examples were a beam of laser light instead of a Slinky, and the observer had been running at a relativistic speed (meaning a speed close to the speed of light), the velocity of the light, both students would measure exactly the same velocity for the light!



In other words, the velocity of the beam of light observed by each student would be *c*.

Because the speed of light (in a vacuum) is a constant, we use the variable *c* (which stands for "constant") to represent it in equations.

This idea seemed just as strange to 19th century physicists as it does today, and most physicists did not believe Maxwell for more than 45 years, until Albert Einstein published his theory of special relativity in 1905. However, several experiments have confirmed Maxwell's conclusion, and no experiment has ever successfully refuted it.

Light travels through a vacuum (empty space) with a velocity of exactly $2.997\,924\,58 \times 10^{8} \frac{\text{m}}{\text{s}}$. However, while the speed of light does not depend on the reference frame, it does depend on the medium it is traveling through. When light travels through matter, (*e.g.,* air, glass, plastic, *etc.*), the electric permittivity and magnetic permeability of the medium are higher, which makes the velocity slower.

The degree to which light bends as it passes from one medium to another is the medium's *index of refraction*, which is equal to the ratio of the speed of light in the medium to the speed of light in a vacuum. Refraction and index of refraction are covered in Physics 2.