Speed of Light

Unit: Special Relativity

MA Curriculum Frameworks (2016): N/A

AP® Physics 2 Learning Objectives: 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:

If the principle of relativity is true, it must be true for all measurements and all reference frames, including those involving light.

In 1864, physicist James Clerk Maxwell united four calculus equations involving magnetic and electric fields into one unified theory of light. The four equations were:

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 as they travel through space.

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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:

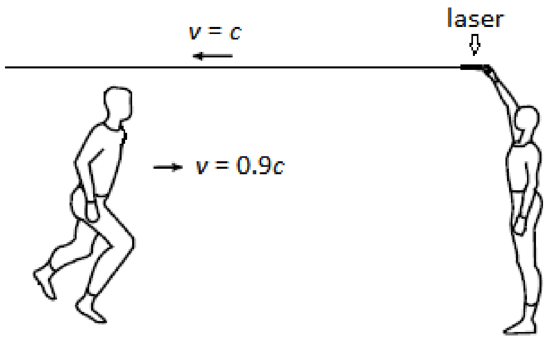
$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} = 2.997\,924\,58 \times 10^8\ \tfrac{\text{m}}{\text{s}}\ ^{*}$$

Both μ_0 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.

If the wave in the above relative velocity examples was a beam of laser light instead of a Slinky, and the observer was 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!



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 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).

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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, when 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 $2.997\,924\,58\times10^{8}\,\frac{\text{m}}{\text{s}}$. However while the speed of light does not depend on the reference frame, it does depend on the medium it is traveling through. (For more information, see the *Refraction* section on page 497.) When light travels through matter, (*e.g.,* air, glass, plastic, *etc.*), the velocity can be substantially slower.

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