Physics Notes

Note 24

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On the Physical Meaning of the Speed of Light in Vacuum

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Abstract

Electrical engineers in general, and electromagnetists in particular take for granted that the speed of light in vacuum is 299,792,458 m/s or approximately 3 x 10^8 m/s. Mankind has defined the units of length and time. In the International System of Units (SI) [1, 2], the speed of light, denoted as *c*, is defined by an exact numerical value. The SI definitions of the meter and second are examined here, in their historical context. The meter is no longer based on artifacts in Paris, France. Historical evolution of the meter is examined. This raises questions about whether it reflects a fundamental property of nature or a consequence of human-defined units. This physics note is meant for engineers and demonstrates that while the numerical value of *c* depends on definitions of length and time, its physical role is invariant and fundamental. Starting from Maxwell's equations, a finite propagation speed emerges naturally. We review the Lorentz transformations from invariance of this speed and show that the spacetime interval is the true invariant quantity. The results establish that *c* establishes the causal structure of spacetime and is not merely an artifact of unit definition.

I. Introduction

The assignment of an exact value to the speed of light in SI units introduces a conceptual tension. This question arises because both length and time are human-defined units. We start with the evolution of the definitions of units of length and time.

Table 1. Evolution of the Definition of one Meter

Year	Basis of definition	Explanation
1790s	Geodetic Definition of meter	Fraction of earth's meridian Ten millionths of the distance of the equator from the north pole along a meridian 1 meter = 10^{-7} x (Earth's circumference /4) m = 10^{-7} x (π x Earth's diameter/4) m = 10^{-7} x (π x 12.8 x10^{6} / 4) m ~ 10^{-7} x (10^{7}) m ~ 1 m
1889	Prototype artifact	Platinum-Iridium Bar maintained by International Bureau of Weights and Measures in Sèvres, France
1960	Spectroscopic standard	A specified number of wavelengths of light emitted by Krypton-86.
1983	Speed of light definition	Meter is defined as the distance traveled by light in (1/299,792,458) seconds. ***This definition reflects the invariant feature of nature.***
2011	Proposal	To define SI fully in terms of seven natural constants
2017	Publication	Updated values of constants are published.

Table 2. SI Definition of a Second [3]

Year	Basis of definition	Explanation
Before 1967	Earth's rotation	Not stable
1967	Atomic transition in Cesium	A Cesium-133 atom can flip between 2 energy states. The radiated frequency is 9.192631770 GHz (X band) $E = h\upsilon$ = 6.09 x 10^{-24} J = 3.8 x 10^{-5} eV (quite small) 1 second = exactly 9,192,631,770 oscillations of this atomic process.

We observe that there is a conceptual shift in the definition of meter and second. This progression reflects increasing alignment with invariant physical phenomena. Speed of light no longer depends on the definition of meter, but the meter is now defined by how long light travels in vacuum in (1/299,792,458) seconds. Second is defined by an atomic transition. Speed of light is fixed, and the meter is derived from it. The absoluteness of the speed of light is not its numerical value but its role in physics. Some physicists set $c = 1$. This means 1 second = 299,792,458 meters. In this case, meter and time have same units. Speed of light c maybe seen as a conversion factor between space and time. In relativity, space and time are not separate, they together form spacetime.

One can think of two scenarios. Firstly, if you are moving at a speed u and throw a ball with speed v, the ball travels at a speed $(u + v)$. Secondly, a thought experiment of a person on an escalator moving at a speed v and turning on a flashlight. You would think light has to travel at a speed of $(c + v)$. This is also exhibited in *Einsteinhaus* (Einstein Museum) in Bern, Switzerland.

According to theory of special relativity, person on the escalator measures light speed as c. An observer off the escalator also measures c and not $(c + v)$. Something must give and time dilates. Moving clocks run slower. Instead of simple addition of $(u + v)$, relativity gives

$$u' = \frac{u+v}{1+\frac{uv}{c^2}} \quad ; \qquad if\ u = c, \qquad u' = \frac{c+v}{(1+\frac{v}{c})} = c \tag{1}$$

where u' = measured velocity of light in a moving frame of reference.

This expression reduces to simple addition if u and v are small compared to c, as in the case of a moving person throwing a ball. We try to explain this absoluteness of c via Maxwell's equations.

Classical or Newtonian mechanics predicts additive velocities. Therefore, observers in relative motion must measure different speeds of light. However, experiments such as Michelson-Morley [4] conclusively demonstrate invariance of speed of light in vacuum. It is noted that Michelson-Morley experiment is a two-way measurement of c, that requires only one clock with no synchronization problem. This measures the average value of c over the round trip and not the individual forward and backward speeds. To measure one-way measurement of c, one requires two perfectly synchronized clocks and cannot be measured independently. Einstein [5] postulated when he said, "*Light propagates in empty space with a definite speed c, independent of the motion of the source or observer*". This postulate makes physics simple and symmetric, Maxwell's equations [6] become symmetric, and Lorentz transformation [7] takes simple form. Under non-Einstein postulation, time derivative changes in Maxwell's equations and wave equations become anisotropic! Without this postulate, one way c becomes direction dependent, but two-way speed is still c. One may conclude that the two-way speed is experimentally verified, but one way speed is postulated by convention.

Einstein's convention of simultaneity is somewhat analogous to gauge freedom in classical electrodynamics [8]. Choice of gauge alters the potential without affecting observable electromagnetic fields. Likewise, clock synchronization modifies the one-way speed without altering the measurable quantities. Einstein's synchronization convention is like a particular choice of gauge that results in symmetry and isotropy.

2. Speed of light in Maxwell's equations

Maxwell's equations [6] precede relativity, and show that the electromagnetic waves travel in vacuum with a speed *c* given by

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} \tag{2}$$

where μ_o and ε_o are respectively permeability and permittivity of vacuum.

The speed of the electromagnetic wave and light - which is also an electromagnetic wave, is a function of the properties of vacuum and has nothing to do with the observer. If different observers measured different speeds, Maxwell's equations would look very different. Nature enforces same speed of light for all observers resulting in spacetime adjustment.

The absoluteness of c comes from invariance of spacetime interval.

$$s^2 = c^2 t^2 - x^2 - y^2 - z^2 \tag{3}$$

This quantity is invariant to all observers. Different observers may disagree on space and time but agree on this combination that involves the speed of light *c* in vacuum.

The paradox is as follows. Before relativity, classical mechanics predicted addition of speeds in the two scenarios considered above, but Maxwell's equation preceded relativity and predicted a fixed speed of light in vacuum. Einstein [5] made a radical move by flipping the logic. There is no need to modify Maxwell's equation, but we need to modify space and time, resulting in time dilation and length contraction, so that *c* remains absolute. This invariance across inertial frames also leads to simple Lorentz transformation discussed below.

3. Lorentz Transformation [7]

Special Relativity postulates that the laws of physics are the same in all inertial frames and *c* is invariant across all observers.

Let us consider two inertial frames *F* and *F'* with relative velocity *v* along the *x* coordinate. Wave equation maintains its form leading to

$$\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} = \frac{\partial^2}{\partial x'^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t'^2} \tag{4}$$

Assuming linearity, $x' = ax + bt, \quad t' = dx + et$ leads to $x^2 - c^2t^2 = x'^2 - c^2t'^2$ (5)

Resulting in

$$x' = \gamma(x - vt), \qquad t' = \gamma\left(t - \frac{vx}{c^2}\right) \tag{6}$$

where $$\gamma = \frac{1}{\sqrt{1-(v^2/c^2)}} \quad \text{(becomes 1 if } v << c\text{)} \tag{7}$$

One might say space and time adjust themselves so that c remains constant, and thus c is a conversion factor between temporal and space coordinates. Its numerical value is less important than its role in physics.

4. Summary

Although the numerical value of c depends on chosen units, its invariance arises from:

- Maxwell's equations
- Structure of spacetime
- Experimental observation
- Changing units alters numbers, not physics.

The speed of light is not merely a defined constant. While its numerical value depends on human-defined units, its physical role is fundamental. It governs causality, defines spacetime structure, and constrains physical laws. The modern SI definition reflects this reality rather than creating it.

References

[1] BIPM, The International System of Units (SI), 9th edition, 2019.

[2] T. J. Quinn, "From artefacts to atoms: the BIPM and the search for ultimate measurement standards," *Metrologia*, vol. 31, pp 515-527, 1995.

[3] General Conference on Weights and Measures, Event (1967-68); this is when the second was redefined from astronomical time to atomic time.

[4] A. A. Michelson and E. W. Morley, "On the Relative Motion of the Earth and the Luminiferous Ether," American Journal of Science, vol.34, 1887, pp 333-345.

[5] A. Einstein, "Zur Elektrodynamik bewegter Körper," Annalen der Physik, vol. 17, pp. 891–921, 1905. (English: "On the Electrodynamics of Moving Bodies").

[6] J. C. Maxwell, A Treatise on Electricity and Magnetism, Oxford University Press, 2 volumes, 1873.

[7] H. A. Lorentz, "Electromagnetic Phenomena in a System Moving with Any Velocity Less Than That of Light," proceedings of the Royal Netherlands Academy of Arts and Sciences, 1904.

[8] D. V. Giri, F. M. Tesche and M. A. Morgan, "Uniqueness of Electromagnetic Fields Using Velocity-Dependent Gauge Potentials,' IEEE Transactions on Antennas and Propagation, Volume 71, No. 4, April 2023.