

The principle of constancy of the speed of Light in free-space - a postulate?

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Abstract: In the present paper discussion has been made whether to accept the constancy of speed of light in free-space as a postulate of the Special Theory of Relativity (STR). It has been argued that all the properties associated with free-space (e.g. electric permittivity and magnetic permeability of free-space) are basic universal constants. As a consequence the principle of constancy of the speed of light can be derived from Maxwell's theory of electrodynamics with the aid of the first postulate of STR.

Recently theory of 'time varying speed of light' has been proposed independently by Moffat [1] and Albrecht and Magueijo [2] as an alternative of Inflationary Cosmological model. Several other authors also advocate for such hypothesis from different grounds [3-4 and references therein] . Such a radical suggestion, however, directly contradicts not only the basic concept of the Special Theory of Relativity but also many fundamental ideas of physics like conservation of energy and momentum. Many of the foundations of today's physics are required to be changed to incorporate the idea of time varying speed of light. Thus this theory leaves us in an uncomfortable situation. The cause of the time variation of the speed of light, however, has not been discussed in those works; rather it has been introduced as a postulate. Moreover nothing has been found so far from any physical consideration which goes directly against the Special Relativity. In this context it is worthy to examine the physical basis of the concept of the universal constancy of speed of light in Special Relativity.

As is well known, the Special Theory of Relativity is based on two fundamental postulates [5-10]. The first one is the principle of relativity which states that [5] "the laws of nature are in concordance for all inertial systems". The other postulate is about the velocity of light in vacuum and the idea was quite radical. It states that [11] "Light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body". This postulate together with the principle of relativity implies that the speed of light in free-space is the same for all observers, independent of the relative motion of the light source and observers. Because this postulate

destroys the long standing concept of time as a universal variable (independent of spatial coordinate), many attempts (for example see reference 6,12) were made (finally without success) to develop theories that would explain all the observed facts without this postulate. The first postulate is evidently one, which stands on the firm ground of reasonableness. But the same is not true for the second one. It is difficult to accept the idea of constancy of the speed of light without any question. However, the success of the STR in explaining and predicting experimental facts and its internal consistency give an indirect proof of its two postulates. Thus it is essential to insist that such a fundamental idea as the invariance of the speed of light in vacuum should be derivable from the simple and more basic assumptions or physical laws.

In relativity we always deal with relative motion between objects. An observer or a source of signal can have velocity with respect to an arbitrary medium through which the signal is transmitting. One can easily measure it by first attaching a reference frame with the medium so that the particles of the medium are at rest with respect to the reference frame and then by measuring the displacement of observer/source with respect to the time of the reference frame or vice versa. But free-space has a special and significant place in the case of relative motion. Is it possible to measure relative motion between an object and free-space ? For this one has to note the time variation of position of a particular point of the free-space with respect to the object. But one cannot mark a point of the free-space without placing some physical object at that point i.e. to recognize a point of the free-space one has to violate the matter freeness property. So relative motion between free-space and an object does not exist. And hence properties of free-space should not depend on the state of motion of an observer. Thus if a space appears to be matter free for an observer it must remain matter free for all observers irrespective of their state of motion. In other words the matter freeness property of the space is absolute. As a consequence the inherent physical properties of the free-space will be same with respect to any observer.

One obvious question is that how one could associate physical properties with empty space. However at present it has been realized from the study of gauge theory that the vacuum has rich mathematical structure with associated physical consequences. One simple example is Aharonov-Bohm effect (13) which owes its existence due to the non-trivial topology of the vacuum.

So values of ϵ_0 and μ_0 , which are the electric permittivity and magnetic permeability of free space respectively, will be the same for all observers i.e. ϵ_0 and μ_0 are universal constants. In fact *all the physical quantities* that are

associated with the properties of free-space will have the same value in any reference frame. One might ask that ϵ_0 and μ_0 are regarded as universal constants for long; so what is new in the above statement? In that case we wish to refer the work of Sumner [4] where permittivity of free-space is considered as a function of time. Our point is that one can not just define a physical quantity as universal constant. One can of-course make such postulate to build a new theory and in that case the success of that theory will in turn give indirect proof of the initial assumption. But from other physical consideration that assumption might have to change. As for example Gravitational constant G is regarded as an universal constant in General Relativity but to make the theory of gravitation compatible with Mach's principle, G is considered as a function of space and time in Brans-Dicke scalar-tensor theory [14]. Similarly Bekenstein [15] constructs a theory based on the postulate that electric charge depends on space-time point to accommodate time variation of the fine structure constant. In the later case the principle of conservation of charge is violated. Here we have tried to provide physical reason behind the constancy of ϵ_0 and μ_0 .

The origin of the constancy of the speed of light in inertial frames lies in electromagnetism. The success of Maxwell's theory to explain the relevant observed facts has established it as the proper theory of electromagnetism. A basic feature of Maxwell's equations for the time-varying electromagnetic field is the existence of travelling waves, that carry energy from one point to another. It follows from Maxwell's equations that each of the six Cartesian components of \mathbf{E} and \mathbf{B} separately satisfies the wave equation of the form

$$\nabla^2 u - \epsilon_0 \mu_0 \partial^2 u / \partial t^2 = 0 \quad \dots(1)$$

where u is a scalar and can stand for one of the components of \mathbf{E} and \mathbf{B} . It is obvious that the above equation resembles the general wave equation of Minkowski space

$$\nabla^2 u - 1/v^2 \partial^2 u / \partial t^2 = 0 \quad \dots(2)$$

and it shows that the field vectors \mathbf{E} and \mathbf{B} are propagated in free space as waves at a speed equal to

$$c = 1/\sqrt{(\epsilon_0 \mu_0)} \quad \dots(3)$$

According to the first postulate of STR all inertial frames are equivalent with

respect to physical phenomena, which means the laws of physics expressed in equations will have the same form in all inertial frames. So in the primed coordinate frame (x', y', z', t') , which is moving with a constant velocity with respect to the unprimed coordinate frame (x, y, z, t) , the equation (1) will preserve its form. Thus

$$\nabla'^2 u' - \epsilon_0' \mu_0' \partial^2 u' / \partial t'^2 = 0 \quad \dots(4)$$

Comparing with equation (2) it becomes obvious that to an observer of unprimed reference frame the electromagnetic field vectors \mathbf{E}' and \mathbf{B}' are propagated in free-space with a velocity

$$c' = 1/\sqrt{(\epsilon_0' \mu_0')} \quad \dots(5)$$

where ϵ_0' and μ_0' are values of the electric permittivity and magnetic permeability respectively of free space as measured by an observer of primed reference frame. But as we know that ϵ_0 and μ_0 have the same value in all reference frames so c' must be equal to c i.e. the speed of light or rather of an electromagnetic wave is the same in all inertial frames.

So we need not to consider the principle of invariance of the speed of light as a postulate. If Maxwell's theory is the proper theory of electrodynamics, as is supposed to be, then the principle of the constancy of the speed of light follows automatically from Maxwell's equations provided we assume that the principle of relativity is true. And even in more fundamental way it is found that ϵ_0 and μ_0 and all other physical quantities associated with matter free-space are constants for any observer. Moreover only the postulate of constancy of the speed of light in all inertial frames can not keep the Maxwell's equations invariant under Lorentz transformation. For the invariance of the Maxwell's equations ($\partial F_{\mu\nu} / \partial x_\nu = \mu_0 J_\mu$, where $F_{\mu\nu}$ is the electromagnetic field tensor and J_μ is four current vector) under that transformation it is also essential that the value of μ_0 is same in all reference frames.

The conclusion of the universal constancy of all physical quantities associated with free space might have many interesting consequences. And it seems that this hypothesis can be verified experimentally (if required!) since number of expressions of physical interest in electrodynamics contain ϵ_0 and/or μ_0 and their different functions..

In conclusion of this article the cause of the constancy of speed of light in free-space in all inertial frames has been examined. It has been logically

shown that all the physical quantities that are associated with the free-space are universal constants. Consequently the laws of electrodynamics together with the first postulate of STR imply that the speed of light has the same value in all inertial frames.

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