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The conceptualization of time and the constancy of the speed of light

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Abstract
In this work, we show that the null result of the Michelson–Morley experiment in vacuum is deeply connected with the notion of time. It can be deduced, without any mathematics, from the assumption only that all good clocks can be used to measure time with the same results, independently of the machinery involved in their manufacturing. A second important assumption, intrinsic to the very notion of time, is that clocks measure time in the same way in different frames, i.e., the notion of time is the same in all inertial frames. Under this assumption, we point out that the 'postulate' of constancy of the 'two-way' speed of light in vacuum in all frames independently of the state of motion of the emitting body is also strongly related to the concept of time, together with the existence of a limit speed in the 'rest frame'. This postulate simply results from the construction of clocks where 'tic–tacs' are made by objects travelling with the limit speed, taken to be the speed of light.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Einstein's celebrated paper 'On the electrodynamics of moving bodies' [1] was published precisely 100 years ago. During this time, the *special theory of relativity* established itself as one of the most exciting topics in physics. The challenges and results of *special relativity* are so stimulating that it keeps attracting the attention of physicists and philosophers, fascinating the general public as well. The centenary of special relativity and the 2005 *World Year of Physics* provide the perfect occasion to revisit its foundations. In this work, we suggest that the roots of both the null result of Michelson–Morley experiment and of the postulate of the constancy of the speed of light in vacuum in all inertial frames, independently of the state of motion of the emitting body, rest firmly on the very notion of time.

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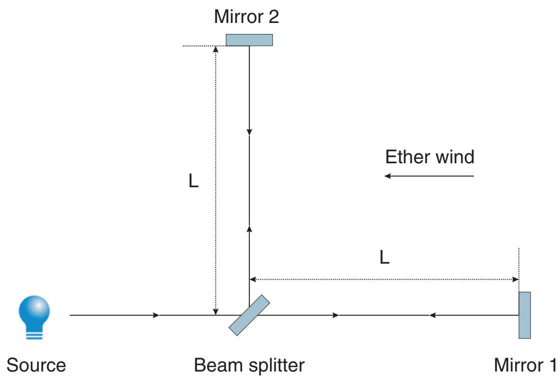

Figure 1. A schematic diagram of the Michelson–Morley experiment.

The structure of this paper is as follows. In the next section, we very briefly describe the Michelson–Morley experiment to introduce the scenario. Section 3 deals with the notions of ‘time’ and ‘clocks’. Finally, in section 4 we consider how the null result of the Michelson–Morley experiment and the postulate of the constancy of the speed of light in vacuum are strongly related to the concept of time.

2. The Michelson–Morley experiment

As is well known, at the end of the nineteenth century several scientists admitted that light waves move through a light ether and that the speed of light in vacuum was c only in a special, absolute frame at rest with respect to this ether. Now, if light moves with speed c only with respect to one special frame, it was supposed that the speed of light on Earth should be faster or slower than c, depending on the way the Earth would be moving through the ether. Several attempts were made to determine the absolute velocity of the Earth through the ether. The most famous was performed by Michelson and Morley in 1887. A simplified scheme of the Michelson interferometer is shown in figure 1. Essentially, a light source emits a beam of light which is divided at a beam splitter. The two resulting beams continue in perpendicular directions to mirrors 1 and 2, where they are reflected, coming back to the same point, where they are recombined as two superposed beams. The details of the experiment are not too complicated to follow and can be found in any physics textbook, such as Feynman [2] or Serway [3]. Basically, what happens is that if the time taken for the light to go from the beam splitter to mirror 1 and back is the same as the time from the beam splitter to mirror 2 and back, then the two beams would reinforce each other. However, if these times differ slightly, an interference pattern should be formed. If the interferometer is at rest (i.e., in the ether frame) and in vacuum, the times should be precisely equal. But if it is moving with a certain speed, from the Galilean law for addition of velocities it was expected that they would be different. Yet no significant time difference was found: it seemed the speed of the Earth through the ether could not be detected. This was of course a puzzling issue, which was addressed by Lorentz in 1895 [4]. He suggested that all moving bodies contract in the direction parallel to their movement through the ether. Lorentz showed that if the length of a moving body is contracted by a factor $\sqrt{1 - v^2/c^2}$, and this contraction occurs only in the direction of the motion, then the null results of the Michelson–Morley experiment would be readily explained. A rather similar hypothesis of a change in the length of material bodies had been formulated independently by Fitzgerald in 1889 [5], who promoted his deformation

Figure 2. The Feynman light clock.

idea in his lectures and correspondence. Einstein's special relativity solves the problem of the null result of the Michelson–Morley experiment by postulating that the speed of light is constant and independent of the speed of the source not only in a preferred ether frame, but in *all* inertial frames. The Michelson–Morley experiment is thus related to the postulate of the constancy of the speed of light in vacuum and plays a central role in special relativity, appearing in almost all books presenting the subject.

3. Time and clocks

It is likely that we will have a hard time in answering, in a simple way, the fundamental question 'what is time?'. Interestingly enough, this difficulty in defining in words what time is, is not of great concern to those beginning the study of physics, since we know how to measure it! Time is what is measured with clocks. Therefore, the 'only' things needed to proceed are clocks.

Let us for now follow Einstein [1] and restrict the analysis to

> a coordinate system in which Newton's mechanical equations are valid. To distinguish this system verbally from those to be introduced later, and to make our presentation more precise, we will call it the 'rest system'.

Of course, within the framework of Einstein's relativity any inertial system can be taken as the 'rest system', but it is interesting to keep in mind the point of view widely accepted by the end of the nineteenth century, when this 'rest system' was identified only with the preferred ether frame. The argumentation developed in this work is very general and is valid in both views. We will further confine the discussion to clocks in 'vacuum', in order to avoid the problem of the interactions between clocks and the surrounding medium. In principle, any periodic phenomenon may be associated with a clock. Galileo even used the rhythm of his heartbeat as a clock. This raises the question of how we know whether the time intervals given by a certain clock are really equal. The truth is that we do *not* know. What is possible is to compare the readings of different clocks (see below). Then, using these comparisons and with the help of theoretical arguments about the laws ruling each of the periodic phenomena involved, we can decide which clock is more trustworthy.

One very simple clock is Feynman's light clock [2], schematically depicted in figure 2. It consists of two mirrors vertically aligned and a light source close to one of the mirrors. At

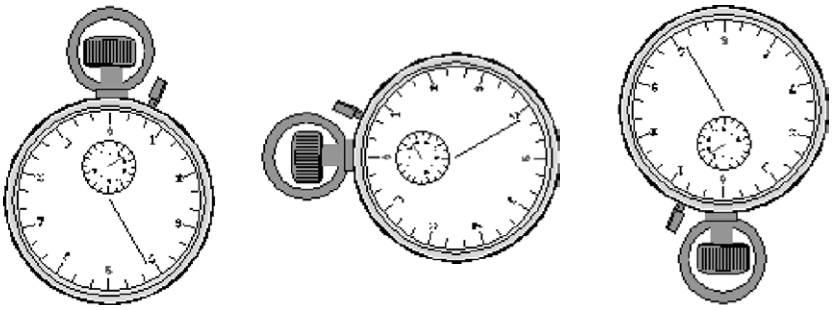

Figure 3. Identical clocks with different space orientations measure the same times.

a certain instant the source emits one photon in the direction of the other mirror. The photon is continuously reflected by both mirrors, making a 'tic' each time it is reflected on the upper mirror, and a 'tac' each time it is reflected on the lower one. The unit of time is then defined by a complete 'tic–tac'. Note that it is not rigorous to define the unit of time with just the 'tic' or just the 'tac', because this would involve the additional assumption that they are equal. This assumption is generally accepted, but it is by no means obvious nor even necessary, as pointed out in [6, 7]. Such discussion is far beyond the purpose of the present work and we simply want to stress that the periodic movement corresponds to the complete 'tic–tac'. That being so, for a general definition of time this is the time interval that must be considered.

It is implicitly assumed that time passes independently of the type of clocks we use to measure it. Therefore, we expect that clocks built upon different phenomena, when in the same location, will mark the same times. This is of course an assumption, even though it is what we expect. In any case, it can be verified by experiment. Up to now there is no reason to suspect that different clocks in the same place do not provide the same time readings, independently of the machinery involved in their construction, as long as they are precise enough. If any good clock can be used to measure time, then the time measurements of a certain clock do not depend on its *orientation*. Even if two equal clocks with different orientations may be regarded as two different clocks, they should still measure the same time intervals (figure 3). If our notion of time is correct, this must be true not only in the 'rest system', but in any 'moving' inertial frame as well, since the clocks used to measure time in these frames are exactly equal to those used in the 'rest system'.

4. The constancy of the speed of light

We are now ready to discuss the Michelson–Morley experiment and the postulate of the constancy of the speed of light. Consider two Feynman light clocks, exactly equal, placed side by side. The particular periodic movement involved in Feynman clocks repeats itself after a complete 'tic–tac', corresponding to a *round trip* of light from one mirror to the other and back. The time unit is one tic–tac and is the same for both clocks. Now rotate one of the clocks by 90°, as shown in figure 4. What happens? If time does not really depend on the clocks used to measure it, if time does not depend on the orientation of clocks, then the complete tic–tac of both clocks is still the same. But two Feynman clocks rotated by 90° are no more no less than the Michelson–Morley interferometer! Therefore, the times light takes to go along each arm of the interferometer and back *must* be the same. This must be true for the 'rest system' as well as for any 'moving' inertial frame. In other words, in *each* inertial frame the *two-way* speed of light is constant. Once more, note that to keep the argument completely general we

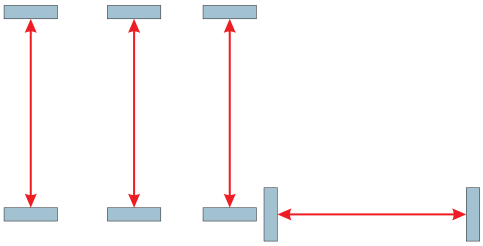

Figure 4. Two similar Feynman light clocks give a complete tic–tac exactly at the same instant both when (a) they are side by side and (b) one of them is rotated by 90°.

must use the two-way speed of light, which corresponds to the average speed of light when it makes a round trip.

As we have just seen, the null result of the Michelson–Morley experiment is deeply connected to the notion of *time* and is actually a confirmation that light clocks are good clocks.

The Michelson–Morley experiment shows that in vacuum light takes the same time to go up to the mirrors and back in both arms of the interferometer (see figure 1), so it corresponds to the assertion that in *each* particular inertial frame the two-way speed of light is the same in all directions. But the experiment does not tell us that the speed has the same value in *all* inertial frames. We shall now see that this constancy is also implied by the fundamental concept of time.

Imagine a Feynman-like clock with bullets. The argument given above is related only to time measurements and equivalence of clocks, not with *light* clocks. It can be applied to the clocks where bullets travel instead of light rays and guns replace the mirrors. Therefore, in *each* inertial frame the two-way speed of bullets must be the same, otherwise the tic–tacs given by two bullet clocks rotated by 90° would be different. What is different with light is that, contrary to bullets, its two-way speed is the same in *all* inertial frames, *independently of the speed of the source*. This very striking fact is connected to c being a limit speed in the 'rest system', as we will now show.

Consider again a Feynman-like clock with bullets. We already know that in any particular moving inertial frame S', say a train that is passing through a station, the two-way speed of bullets fired in that frame is the same, no matter the direction they are travelling in. Now, if the one-way speed of these *same* bullets, which were shot with guns fixed in the train, is measured in the station, one obtains a different value. Thus, the *same* bullets travel with *different* one-way speeds in different frames. In this sense, one can say that the one-way speed of bullets is *not* the same in *all* inertial frames. However, suppose now that the bullet clock is taken from the train to the station and bullets are again shot. It is precisely the same clock, which does 'tic–tac' and measures time precisely in the same way. Note that *time is actually measured with distances* and that since a clock involves a periodic movement, time units—the tic–tacs—are defined with average two-way speeds. Thus, if bullets move in S' with a certain two-way speed v' along a straight line, the total distance x' they travel in a round trip in S' is related with the elapsed time t' via $x' = v't'$. For instance, if the round trip takes 1 m and the two-way speed is 1 m s^{-1}, one second passes in each tic–tac. If the same clock is used in a second inertial frame S'', in each tic–tac bullets now travel a distance x'', which corresponds to a certain time t''. Of course $x'' = v''t''$, where v'' is the two-way speed of bullets in S''. But, if the clock measures time in the same way as before, then this correspondence between distance and time must be done in exactly the same way, i.e., $v' = v''$ and the two-way speeds of bullets must be the same in both frames. Hence, the two-way speed, measured in the station, of bullets fired in the station, must be the same as the two-way speed, measured in the train, of bullets fired in the train. This is intrinsic to the very notion of time: it only means clocks measure time in the same way in different frames: the notion of time is the same in all inertial frames. So there is also a 'constancy' of the two-way speed of bullets in *all* inertial frames! But this constancy refers to *different* sets of bullets, the bullets fired in the train and the bullets fired in the station. *Different* bullets travel with the *same* two-way speed in different frames. Evidently the argument is valid not only for bullets. Therefore, the two-way speeds of *any* kind of objects must be the same in *all* inertial frames, as long as we are referring to *different* objects of the same kind, emmitted by perfectly equal devices at rest in relation to the different frames. This is true for bullets as well as for light.

The final step is the issue of a limit speed. Assume that such a limit exists: that no object travelling in the 'rest system' can have a two-way speed higher than a certain value c (it is worth observing that, in principle, the one-way limit speeds can have different values in different directions, as long as the two-way value is c [6]; in any case, equal or different, these one-way speeds are still limit one-way speeds in the 'rest system' for particular directions of space). For all objects moving with speeds lower than the limit speed, the constancy of their two-way speed in all frames refers to *different* objects, such as the 'bullets fired in the train' and the 'bullets fired in the station'. For simplicity, let us make the station coincide with the 'rest frame' and refer speeds to this frame. If the bullets are fired in the direction of the head of the train, bullets shot from the train always have a higher speed than the bullets shot from the station with a perfectly equal gun. Now pick a more powerful gun, which shoots bullets at higher speeds. The same thing happens. The bullets shot from the train always have a higher speed than the bullets shot from the station, which, in turn, move faster than the bullets shot with the less powerful gun. The process can continue by successively taking more powerful guns. For a really powerful gun, the speed of bullets fired in the station can be very close to the limit speed. But in the 'rest frame' of the station the bullets fired from the moving train cannot have a speed higher than the limit speed! Therefore, in this case the bullets shot from the train will move almost imperceptibly faster than the bullets shot from the station. And so, if an object emitted from the 'rest frame' moves with the limit speed, it will also move with the limit speed when emitted from a 'moving' inertial frame: objects travelling with the limit speed must do so independently of the velocity of the emitting source. In this way, the existence of 'objects' moving with the same speed independently of the speed of the source is directly connected to the existence of a limit speed in the 'rest frame'. Observe that the discussion above also illustrates physically the fact that the Galilean addition law for velocities cannot be valid, a point that was central to Einstein's own development of special relativity.

What is special about light is that it moves with the limit speed. That being so, and contrary to bullets, if two light rays are emitted simultaneously, on the same position in space, one in the train and the other in the station, there is no difference between the two rays! Light propagates on the 'rest frame' with the same speed independently of the velocity of the source emitting the light, and actually both rays can be seen as forming the *same* object. It was argued above that different objects of the same kind have the same two-way speed in different frames. This is true for bullets as well as for light. But with light the distinction between 'different' light rays is artificial. The two-way speed of the *same* light rays must then be constant in different inertial frames. This speed must be the limit speed in the 'rest frame'. Because different objects, emitted from different inertial frames, collapse into the same object if and only if they travel with the two-way limit speed c. This distinctive feature of the limit speed that its two-way value is the same in all inertial frames regardless of the speed of the source, makes it the privileged way to convert spaces to times through $x = ct$. All the argumentation was made only on the basis of our notions of time and clocks. In this sense, the limit speed can somehow be seen as 'the speed of time'.

5. Summary and conclusion

We have shown that both the null result of the Michelson–Morley experiment and the postulate of constancy of the two-way speed of light in vacuum are a direct consequence of the fundamental notions of time and clocks. They can be obtained under three very reasonable assumptions: (i) all good clocks can be used to measure time, independently of the periodic physical phenomena they are built upon; (ii) time is measured in the same way in all inertial frames, i.e., if a particular clock can be used to measure time in the 'rest system', a similar clock can be used to measure time in 'moving' inertial frames; (iii) a limit speed exists in the 'rest system'.

The question of the possible constancy of the one-way speed of light in vacuum is related to the one century long question of a preferred frame versus 'equivalence' of all inertial frames, and is left for a forthcoming paper. However, the arguments presented here are completely general and have to be true in both scenarios.

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