the general science journal

The Moving Light Clock: Which Way the Photon Goes?

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Time dilation and length contraction are two important effects of Special relativity (SR). These two effects depend upon the second postulate of this theory that the speed of light c $(=2.99792\times10^8$ m s$^{-1})$ is the same in all inertial frames of reference [1].

Many physics textbooks deal with the subject of time dilation. This phenomenon can be demonstrated using a device known as the light clock [1]. The light clock consists of two-plane parallel mirrors M_1 and M_2 facing each other at a distance d apart as in Fig. 1a.

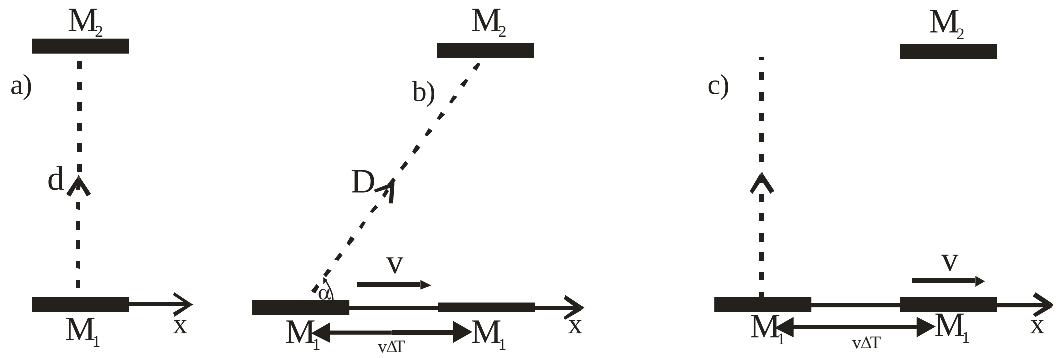

Fig. 1. The SR description of the photon path of the light clock: (a) at rest and (b) traveling along the positive x-axis at the speed v; and, (c) the photon path independent from the motion of the light clock (or from the inertial frames of reference).

The lower mirror M_1 has a light source at the center that emits a photon at 90 degrees in the direction of mirror M_2. For the sake of simplicity, we will consider time for the photon to travel from mirror M_1 to mirror M_2. Of course, you may find all following derivations in many elementary physics texts.

For the light clock at rest, the (proper) time interval is then $\Delta T_0 = d/c$. Now allow the same light clock to be moving with a certain relative speed v horizontally in the direction of positive x-axis, Fig. 1b. Clearly, a photon will now travel the larger distance D and thus it will take a longer (improper) time interval $\Delta T = D/c$. According to SR, ΔT_0 and ΔT are related by the relativistic time dilation expression $\Delta T = \Delta T_0 /\sqrt{1-v^2/c^2}$. Thus, the effects of time dilation only start to become measurable at speeds close to the speed of light c, i. e. at so-called relativistic speeds.

It is important to note here that the angle α between the photon path and the direction of motion of the light clock depends on the v/c ratio, in particular $\cos(\alpha) = v/c$. In other words, α depends of the light clock speed v (or the speed of inertial reference frame) and appears also only measurable at relativistic speeds.

In this derivation, one assumes that the photon travels from M_1 to M_2 when the light clock frame is moving. It appears, virtually, that this assumption is valid when we are dealing a light clock at non-relativistic speeds. In this case, the clock distance $v\Delta T$ is very small compared with the photon distance $c\Delta T$, i.e. $\alpha \rightarrow 90$ degrees. However, for a light clock traveling at relativistic speeds this assumption is ambiguous since these speeds for a man-made object will be unattainable even for the very distant future. Indeed, at present, the fastest rocket system in the world can only reach speeds of up to about 2000 m s^{-1}. According to SR, a stationary observer would observe that the direction of the photon motion is affected by the relativistically fast light clock, being at the angle α relative to this direction, Fig. 1b. Or she/he could observe that the photon is traveling perpendicular to the direction of motion and it is not affected by the moving light clock (or by the moving inertial frame of reference), Fig. 1c. If the latter is correct then the traditional light clock experiments are meaningless.

Finally, it should be noted that SR states that "the velocity c of light in vacuum is the same in all inertial frames of reference in all directions and depends neither on the velocity of the source nor on the velocity of the observer" [Einstein, 1905]. It appears then rather peculiar that the direction of the photon motion would depend on the speed of the inertial frame of reference.

Reference

1. W. Rindler, *Introduction to Special Relativity*, 2nd ed. Oxford University Press, 1991.