The physical meaning of the definition of distant simultaneity

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Abstract

It is a remarkable thing that distant simultaneity has proved over the years to be one of the most contentious and apparently confusion issues in Special Relativity Theory . Einstein defined simultaneity for two reasons . Firstly, to equate the one-way with the two-way speed of light and secondly to explain a natural phenomenon described in his famous train-embankment thought experiment . In the former , distant clocks are synchronized assuming light speed invariance, while in the latter, no assumptions are made regarding the physical nature of light. It turns out that distant events can be defined both simultaneous and separated in time in the same reference frame, leading to the conclusion that light may not behave as we think it does.

Keywords :

Special relativity theory , distant simultaneity, relativity of simultaneity, one-way speed of light , definition of simultaneity

1/ Introduction

The foundations of modern physics are quantum theory and Special Relativity Theory (SRT) . It was in SRT that the necessity for a change in the fundamental principles of physics was recognized for the first time, in particular the concept of distant simultaneity . In Newtonian mechanics (NM) , simultaneity is assumed absolute rendering all speeds, even the speed of light relative, i.e. have different values for relatively moving observers. Einstein realized that if the speed of light were invariant , distant simultaneity could not be absolute . But why did Einstein wanted light speed invariance , emphasizing that in 1905 there existed no empirical evidence supporting this distinct from the experimental successes of Maxwell's electromagnetic theory in general? Indeed, " It is by no means self-evident that light speed invariance is actually realized in nature… ", said Einstein himself in 1907 with regard to the light postulate [i] .

From Maxwell's equations, $\nabla^2 \vec{E} = \mu_0 \varepsilon_0 \dfrac{\partial^2 \vec{E}}{\partial t^2}$ and $\nabla^2 \vec{B} = \mu_0 \varepsilon_0 \dfrac{\partial^2 \vec{B}}{\partial t^2}$, a speed can be deduced $c = \sqrt{1/\varepsilon_0 \mu_0}$. It was the agreement of this calculated velocity with the measured speed of light that caused Maxwell to write : " *light is an electromagnetic disturbance propagated through the field according* *to electromagnetic laws"* , i.e. a changing electric field E induces a changing magnetic field B which in turn induces a changing electric field E inducing ….., at infinitum until absorbed by matter. So, Maxwell's equations seem to set a limit of how fast signals can travel and information be disseminated . On the other hand, such a speed limit does not exist in Newtonian Mechanics , hence seems incompatible with Maxwell's theory of electromagnetism . But how can it be proven that electromagnetic radiation consists of the interplay between changing electric and magnetic fields ? What if light is the movement of electric and magnetic fields oscillating in space but not in time and therefore Maxwell's equations don't apply ? It is argued that if super luminal signals (speeds v > c) existed , then according to the Lorentz transformations , there would exist inertial frames in which cause and effect are reversed and in which the signal is considered to travel in the opposite spatial direction (Rindler W. 2006) [ii] . It is therefore believed that paradoxes of this kind are avoided *if and only if* the speed of light is absolute (Rindler 2006, Sartori 1996) . [iii]. [iv]. [v]. Einstein commented in a paper published in 1907 [vi] : "even though this result (the reversal of cause and effect) does not contain a contradiction from a purely logical point of view, it conflicts so absolutely with the character of all our experience that the impossibility of the assumption v > c is sufficiently proved by this result". However, these arguments proves nothing but the self-consistency of SRT . When simultaneity happens to be absolute after all , then causal paradoxes of any kind can never ever occur .

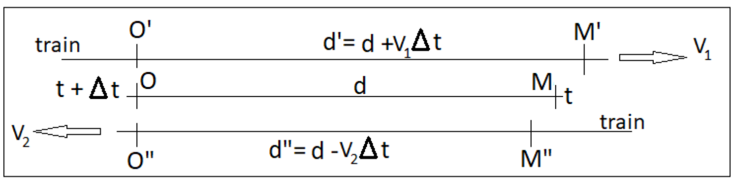
That not only temporal but also spatial measurements depends on the definition of simultaneity follows from the fact that the length of a moving line segment is defined as the distance between the simultaneous positions of its endpoints. However, to quote the philosopher Max Jammer : [vii] " *One of the major problems debated by philosophers of science is the controversial question* of whether the concept of distant simultaneity as defined by Einstein, denotes something factual, empirically testable, or at least unambiguously definable , or whether it refers to merely an object of a convention, that is to an arbitrary stipulation without any factual content, as to which events are to be called simultaneous. If the concept of distant simultaneity is a fundamental ingredient in the logical structure of the theory of relativity but is in reality nothing but a convention, the question naturally arises of whether this does not imply that the whole theory of relativity and with it a major part of modern physics are merely fictions devoid of any actual content ? A positive answer to this question would have disastrous consequences for the philosophical understanding of physics and with it of the whole of modern science.* " end quote. This paper tries to answer this controversial question * , hence the title of this manuscript. Before we go into the argument, let's see where Max Jammer's concerns are coming from .

2/ Three definitions of distant simultaneity

2.1 Measuring the length of a moving line segment .

As mentioned above, the length of a line segment is defined as the distance between the simultaneous positions of its endpoints. Obviously, when the line-segment is moving, the two position measurements must be carried out simultaneously, otherwise the result is guaranteed to be in error . To demonstrate this, imagine two observers O and M , carrying each a clock, at rest on a railway platform a proper distance d apart ,as illustrated in figure 1. These observers have agreed that at time t on their clocks , they will mark their positions onto opposite travelling trains . Let *d'* and *d"* denote the proper distances between respectively O' – M' and O" – M" on the moving trains, then $d' = d + v_1\Delta t = d'' = d - v_2\Delta t$ if and only if $\Delta t = 0$. According to NM and without contradicting experimental evidence, when $d' = d''$, then $d' = d'' = d$

Fig 1 : Opposite moving trains



2.2 Distant simultaneity as defined by Einstein

2.2.1 Einstein's first definition and the one-way speed of light

At a first sight, it would seem that the experimental determination of the speed of light is a single task. It is only necessary to have a source of light emitting from point A and let the light travel the path of length L to arrive at point B. Then, by measuring the time the light takes to travel from point A to B it seems possible to obtain the one-way speed of light simply by dividing the length L by the time difference measured by the two clocks. Still this appearance of simplicity is only an illusion. Pointcaré realized that to measure the initial time, the time of departure of the pulse of light from point A, we need a clock placed at that point. To determine the arriving time, the final time, another clock must be placed at point B. The transit time will then be the time difference of the two readings, if and only if the two clocks are properly synchronized. However, to synchronize clocks, one needs to know the one- way velocity of light (or any other signal) , but to determine the one-way speed of light, one requires synchronized clocks .

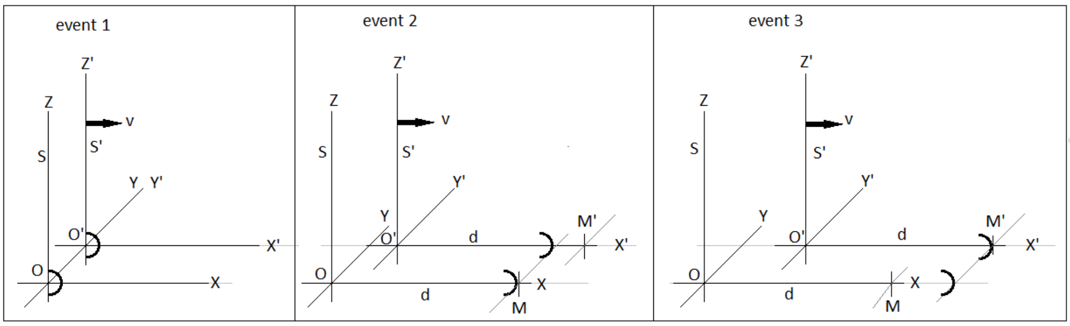
Aware of this circular reasoning , Einstein wrote in his famous 1905 paper on Special Relativity [viii] : "…*we have not defined a common time for A and B, for the latter can now be defined by establishing by definition that the time required by light to travel from A to B equals the time it requires to travel from B to A. Let a ray of light start at the A-time* t_A *from A towards B , let it at the B-time* t_B *be reflected at B in the direction of A, and arrive again at A at A-time* t'_A *, then the two clocks are synchronous by definition if :*

$t_B - t_A = (t'_A - t_A)/2$ where $\frac{2\overline{AB}}{t'_A - t_A}$ denotes the two-way velocity of light c

The importance of this definition of simultaneity in SRT can hardly be over-stressed as demonstrated in the following situation:

Two inertial frames S (x, y, z, t), and S' (x', y', z', t') in standard configuration are moving relatively at speed v along their common x – x' axes . Let observer M be at rest in S at a proper distance d from the origin O on the x- axis and observer M' at rest in S' at the same proper distance d' from O' on the x'-axis. When O and O' coincide, a pulse of light is emitted from light sources at rest at O and O' as depicted in figure 2 (event 1) and where clocks at rest at O and O' indicate identical times : $t_0 = t'_0$

Fig 2 : the relatively moving frames S and S'



Let's imagine that the two pulses travel in unison and thereby confirming that the speed of light does not depend on the movement of its source . Obviously, for the pulses to arrive at M' (event 3) , they already must have passed M (event 2). The not at all trivial question then arises ; why does it takes more time for the pulses to travel from O' to M' in S' than from O to M in S ?

NM explains this natural phenomenon invoking the relativity of the speed of light : Let *T* and *T'* denote the time intervals the pulses of light need to cross the paths respectively O $\rightarrow$ M and O' $\rightarrow$ M' , then *T* < *T'* . Therefore, the one-way speed of light is higher in S than in S' and explains why the pulses reach M before M' :

$$T < T' \Rightarrow \frac{\overline{OM}}{T} > \frac{\overline{O'M'}}{T'} \quad (2) \qquad \text{where} \qquad \frac{\overline{OM}}{T} - \frac{\overline{O'M'}}{T'} = v \quad (3)$$

SRT denies this result based on the assumption that the propagation mode of light is described by Maxwell's equations . That light behaves in our laboratories as illustrated in fig 2 is established experimentally numerous times [ix] . However, as demonstrated above, these experiments by themselves do not prove light speed invariance . This is how the definition of simultaneity " resolves" this puzzle.

Imagine that M sets his clock to read $t_M = t_0 + d/c$ at event 2 and M' sets his clock to indicate $t'_{M'} = t'_0 + d'/c$ at event 3. In SRT, both pairs of clocks, O - M and O' - M' , are synchronous by definition in their rest frames , yielding :

$$T = t_M - t_0 = T' = t'_{M'} - t'_0 \quad \Rightarrow \quad \frac{\overline{OM}}{t_M - t_0} = \frac{\overline{O'M'}}{t'_{M'} - t'_{0'}} = c \qquad (4)$$

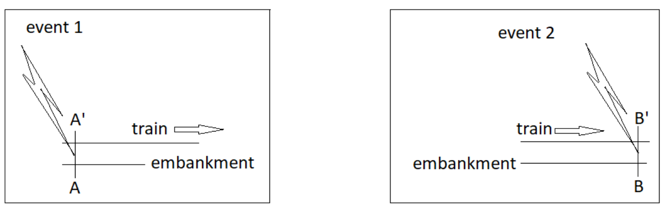
We clearly see that defining simultaneity (synchronizing clocks) this way, guarantees the speed of light to be invariant . Furthermore, because the events 2 and 3 are causally connected, they can't but occur separated in time . As a result, distant events happening simultaneously according to the clocks O and M are guaranteed to occur at different times according to clocks O' and M' , and vice versa . When observers in S and S' then perform such an experiment as described in fig 1 to verify experimentally the synchronicity of their clocks O – M and O' – M' respectively , it's guaranteed that at least in one of these frames $\Delta t \neq 0$. Yet , in SRT, both pairs of clocks are synchronous by definition in their own rest frame . Definitons are neither true nor false but it appears that the definitions 2.1 and 2.2.1 are incompatable and at least one of them seems meaningless physically.

2.2.2 Einstein's second definition of simultaneity without using clocks

In his popular 1917 exposition of relativity , Einstein presented a second definition of distant simultaneity without the use of clocks in the well documented train-embankment thought experiment [x] (figure 3) . In it, he reduces the concept of distant simultaneity to local simultaneity which is unambiguous. Assume, said Einstein , that lightning has struck the rails on a railway embankment at two places A and B far distant from each other. Einstein proposed the following definition of distant simultaneity : " If an observer M, at rest halfway between A and B, perceives the two flashes of lightning at the same time, then they occurred simultaneous . That light requires the same time to traverse the path A to M as for the path B to M is in reality *neither a supposition nor a hypothesis about the physical nature of light, but a stipulation* which I can make of my own free will in order to arrive at a definition of simultaneity ". Emphasizing that this definition does not assume nor imply light speed invariance .

Einstein then continues to demonstrate the relativity of distant simultaneity. This simple demonstration still remains a subject of debate , especially among philosophers of physics [xi] . Yet, it's a simple enough natural phenomenon demanding an explanation.

Fig 3 : Two distant lightning bolts strike down



Imagine that a lightning bolt strikes where A and A' coincide and another one where B and B' coincide. (fig 3) It's a fact of nature that when observer M', at rest halfway between A' and B' on the train , happens to see the two flashes of lightning simultaneously, then observer M , at rest halfway between A and B on the embankment, won't see the flashes simultaneously , or vice versa . **Why** is that ? There seems to be two plausible answers to this question . 1/ because simultaneity isn't absolute but relative : according to the definition 2.2.2, the events 1 and 2 happened simultaneously with respect to train but separated in time with respect to the embankment . 2/ because the speed of light isn't absolute but relative .

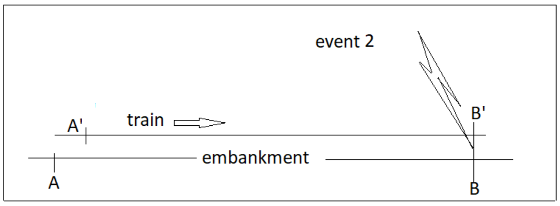
Given that observer M' on the train perceives the two flashes simultaneously, then : $\frac{A'M'}{T_{A'}} = \frac{B'M'}{T_{B'}}$. (5) where $T_{A'}$ and $T_{B'}$ denote respectively the times the light needed to travel from A' to M' and from B' to M'. In SRT, Eq. (5) is true *by definition 2.2.2* while in NM , Eq. (5) is valid if and only if the rest-lengths $\overline{AB}$ and $\overline{A'B'}$ are equal as we saw in 2.1 :

$$\overline{AB} / \overline{A'B'} = \gamma = 1 \quad (6) .$$

On the other hand, according to the definition 2.2.2 , event 2 occurred later than event 1 with respect to the embankment . If this definition does represent reality as experienced on the embankment, then the positions A and A' will certainly not coincide at event 2 as depicted in figure 4 . It's then inevitable that the rest-lengths will be different :

$$\overline{A'B'} / \overline{AB} = \gamma \neq 1 \quad (7) .$$

Fig 4 A and A' don't coincide at event 2 with respect to the embankment



Both explanations answer the "**why**" question above. The only empirically verifiable difference between the two answers is the value of γ. Without knowledge of this value , it remains to be determined whether the definition2.2.2 represents physical reality , hence Max Jammer's concern .

However, as Rindler W. [xii] and Zhang Zhong [xiii] and the physics community in general argue, the enormous success of special relativity theory in contemporary physics has made it impossible to doubt the basic premises of SRT , i.e. that distant simultaneity is relative.

On the other hand, the fact that distant events can be defined to happen both simultaneous and separated in time in the same reference frame, as demonstrated in the following thought experiment, might validate the Eqs. (2), (3) and (6) .

3 / <u>The argument</u> :

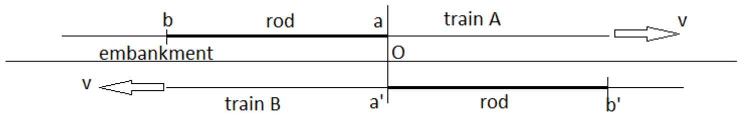
The argument consists of a thought experiment in which 4 light pulses, emitted from different sources, are seen by three relatively moving observers . The aim is to explain why neither of the three observers sees a same pair of light pulses simultaneously .

The conclusion referred to in the abstract, is based on five statements ,numbered $[1]"...",[2]"...",....$, which we will come across in the argument.

3.1 <u>A double train thought experiment</u> :

Consider two very long trains A and B which travel inertially with equal and opposite speed v relative to the embankment . Although the value of the one-way speed v cannot be determined without resorting to a definition of simultaneity , the equality of the speeds can nevertheless be established as follows :

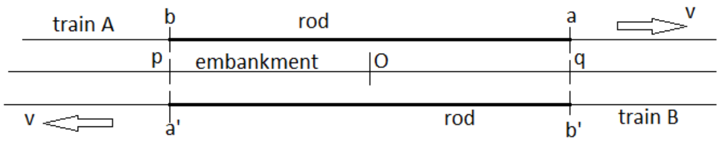
Fig 5 Two trains moving in opposite direction



Let there be a rigid rod at rest in both trains of equal rest lengths with endpoints a and b, and a' and b' respectively . When a and a' coincide at some point O on the embankment , then b and b' will coincide at point O as well , if and only if the trains travel at the same speed with respect to the embankment (fig 5).

It's worth mentioning here an important remark which will relied upon later in the argument : " the meeting of the endpoints of the moving rods (at the points p and q) are simultaneous events with respect to the embankment " (fig 6). As a matter of fact, this is what Einstein demonstrated in a similar thought experiment [xiv] in which he shows that the determination of the simultaneity of spatially separated events can , in principle , be carried out entirely with the help of measuring rods , without the use of clocks .

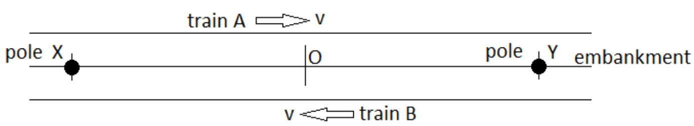
Fig 6 the meeting of the endpoints at the points p and q .



3.2 <u>Determining of the length of a moving line segment</u>

Observers in both trains A and B will project onto their train the positions of two poles X and Y supporting the electric catenary. (fig 7). In other words, they will determine the length of the relatively moving line-segment $\overline{XY}$. Let L be the distance between the poles as measured on the embankment . O denotes an observer at rest halfway between the poles .

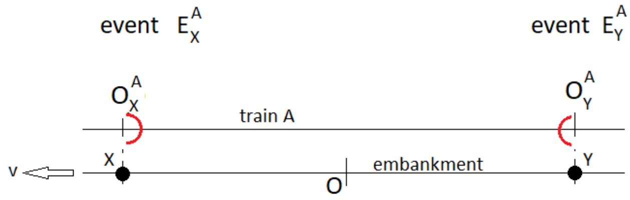
Fig 7 Trains A and B are passing the poles



According to the well-established principle of relativity, observers inside the trains have every right to consider their own train as being at rest . Indeed, every single experiment searching for a preferred frame, yielded negative results [xv] .This implies that when observers in both trains perform a Michelson-Morley's type experiment , both results will be negative . These observers also obtain the same value for ε_0 by taking measurements on parallel-plate capacitors. And since μ_0 has an assigned value , observers in both trains get the same value $c = \sqrt{1/\varepsilon_0 \mu_0}$, etcetera .

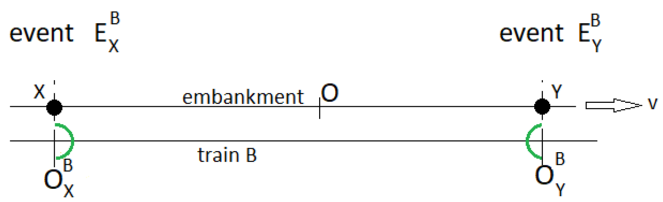
It happens to be that at train A-time t_0^A , observers O_X^A and O_Y^A coincide with respectively pole X and Y while emitting a short pulse of red light . Let the events E_X^A and E_Y^A denote these coincidences (fig 8) . The pulses of light propagate through the confined space of train A and at time t_1^A ,the red pulses meet where observer M_A is sitting . It turns out that M_A sits halfway between his fellow passengers O_X^A and O_Y^A . Statement $[1]$: " because M_A sees the two red pulses simultaneously, the distance L_A between the observers O_X^A and O_Y^A , represents the length of the moving line-segment $\overline{XY}$ as measured in train A " .

Fig 8 The events E_X^A and E_Y^A at time t_0^A as viewed from train A



Observers in train B follow the same procedure. Let it be that at train B-time t_0^B , observers O_X^B and O_Y^B at rest in train B , coincide with respectively the poles X and Y , where they both emit a short pulse of green light. Let the events E_X^B and E_Y^B denote these coincidences(fig 9) . The green light propagates through the train B and at time t_1^B , the green pulses meet where observer M_B is sitting . It turns out that M_B sits halfway between O_X^B and O_Y^B . Statement $[2]$: " because M_B sees the two green pulses simultaneously, the distance L_B between O_X^B and O_Y^B , represents the length of the moving line-segment $\overline{XY}$ as measured in train B ".

Fig 9 the events E_X^B and E_Y^B at time t_0^B as viewed from train B



Note, the only purpose for using different colors is to easily distinguish the pulses emitted in the different trains . The positions of M_A and M_B where the red and green pulses meet , are unknown at time t_0^A respectively t_0^B , hence are not depicted in the figures 8 and 9.

Given that the line-segment $\overline{XY}$ is moving at the same speed with respect to both trains, then: statement $[3]$ " $L/L_A = L/L_B \;\Rightarrow\; L_A = L_B$ " .

When $L_A = L_B$, then ; statement $[4]$: " according to the observers on the embankment, the meeting of the endpoints of the moving line-segments $\overline{O_X^A O_Y^A}$ and $\overline{O_X^B O_Y^B}$, are simultaneous events " .

Let it then be a remarkable coincidence that the meeting of the endpoints occur at the poles X and Y , in analogy with the positions p and q in figure 6 . The occurrences at the poles , i.e. the events eX and eY , are illustrated in figure 10

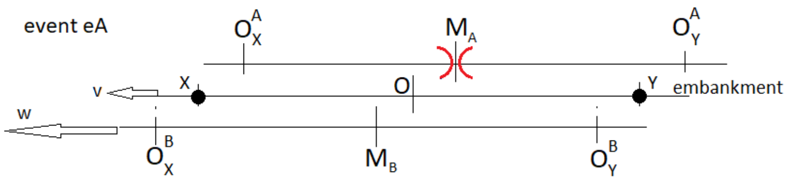
fig 10 Event eX happening at pole X , event eY happening at pole Y

Statement [5] : " $\dfrac{L_A}{2\left(t_1^A - t_0^A\right)} = \dfrac{L_B}{2\left(t_1^B - t_0^B\right)}$ = let's say c " (11) Note the similarity between this equation and Eq. (4) . Contrary to the situation regarding Eq. (4) , events which happen simultaneously according to the clocks in train A (or B) , are not guaranteed to occur separated in time according to the clocks in train B (or A) !

3.3 The physical meaning of definition 2.2.2

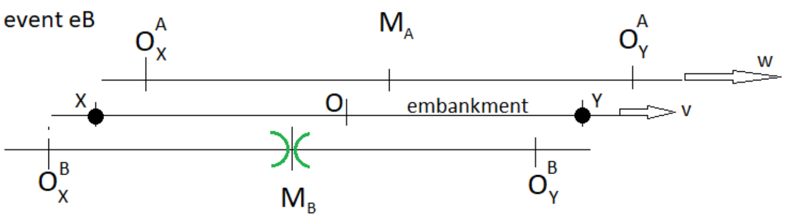
As we've seen in the train-embankment thought experiment, given that M_A perceives the red pulses simultaneously (event eA) , implies (i) that M_B and observer O will see the red pulses in succession (fig 11) .

Fig 11 M_A sees the red flashes simultaneously, M_B and O separated in time



And the fact that observer M_B sees the green pulses of light simultaneously (event eB) implies (ii) that M_A and O perceive the green pulses in succession (fig 12) .

Fig 12 M_B sees the green flashes simultaneously, M_A and O separated in time



From the symmetry of the situation, we infer that O sees the pulses emitted from the approaching bodies O_X^A and O_Y^B simultaneously, as well as those emitted from the receding bodies O_Y^A and O_X^B , implying (iii) that M_A and M_B observe the pulses of these two pairs separated in time.

When we list each pair of light pulses according to whether they are observed simultaneously (group A) or not (group B) , a pattern emerges. There are 6 different pairs consisting of (see fig 10 and 13) :

1/ two red pulses,

2/ two green pulses,

3/ a red pulse emitted at pole X and a green one emitted at pole Y,

4/ a green pulse emitted at pole X and a red one emitted at pole Y,

5/ a red and green pulse emitted at pole X ,

6/ a red and green pulse emitted at pole Y .

Group A :

The pulses emitted by bodies with the same state of motion, are perceived simultaneously . These are :

Pair 1 is emitted from bodies both at rest with respect to, and seen simultaneous only by M_A . Pair 2 is emitted from bodies both at rest with respect to, and seen simultaneously only by M_B . The pairs 3 and 4 are emitted from bodies respectively both approaching and both receding with respect to the embankment and both pairs are seen simultaneously only by O .

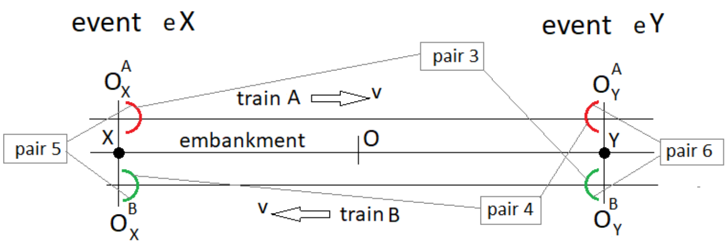
Group B :

The majority of the pairs consist of light pulses which are emitted from bodies with different states of motion (at rest /approaching , at rest/receding, approaching / receding) . The pulses of these pairs are observed separated in time .

Invoking the definition 2.2.2 to explain this pattern, seem to lead to the contradiction mentioned in the abstract . For example , observer M_A sees the red pulses simultaneous and the green ones separated in time . The red and green pulses, therefore , are defined to have been emitted respectively simultaneous and separated in time with respect to train A and vice versa for train B . However, both events eX and eY consist of the emission of a red and a green pulse at the poles X and Y , as illustrated in figure 10. These events , eX and eY, are thus defined to have occurred both simultaneously and separated in time in the same frame , a situation which is physically impossible. Naturally, definitions themselves are neither true nor false but when the definition leads to these paradoxical situations, then definition 2.2.2 must be regarded as physically meaningless and does not represent reality . But there is more:

According to statement $\left[4\right]$, the events eX and eY occur simultaneously with respect to the embankment, (fig 13) , let's say at embankment time t_0 . When the speed of light c is assumed absolute , then it's but self-evident that observer O should see the red and green pulses of light simultaneously at embankment-time $t = t_0 + L/2c$. According to (i) and (ii) however, this does not happen. Moreover, when the speed of light c is assumed absolute, then the observers M_A and M_B should see both the red and green pulses simultaneously as well , which according to (i) and (ii), they don't .The assumption therefore must be false.

Fig 13 eX and eY happen simultaneous with respect to the embankment



On the other hand and without contradicting any experimental evidence, the time order in which the observers O, M_A and M_B perceive the different light pulses, can easily be explained as the result of the speed of light being relative .

4/ Conclusion

Either one or more statements is (are) inconsistent with SRT , or the velocity of light has a different value for relatively moving observers and where the absoluteness of simultaneity prevents causality from ever being violated .

I would strongly emphasize that this result in no way whatsoever presupposes or requires the reintroduction of a hidden preferred reference frame, formerly known as the " luminiferous ether ".

When time is defined as what clocks indicate, then absolute simultaneity does not imply absolute time . Indeed, there exists compelling and unambiguous evidence that accelerating clocks (earth clocks accelerating at 9.81 m/s²) register less time between events compared to inertial clocks (orbiting clocks) .

" … the opposite of a profound truth may well be another profound truth" Niels Bohr

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