LORENTZ CONTRACTION AND DIMENSIONALITY OF REALITY

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ABSTRACT

The purpose of this paper is to show that the Lorentz contraction of a rod is possible only if the rod's world path is a real four-dimensional object. This result demonstrates that special relativity does require reality at the macroscopic level to be a four-dimensional world represented by Minkowski spacetime.

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1 INTRODUCTION

It turns out that a thorough analysis of the Lorentz contraction leads to answers to two unrelated at first sight questions: (i) whether the Lorentz contraction is caused by some forces and, (ii) whether Minkowski spacetime is an abstract mathematical representation of reality which we consider to be an evolving in time three-dimensional world or it is a mathematical model of a real four-dimensional world with time as the forth dimension.

Since the first derivation of the length contraction effect intended to account for the negative result of the Michelson-Morley experiment there has always existed a tempting possibility to explain it in terms of some deformation forces. It is shown in Sections 2 and 3 that this possibility is ruled out since a force explanation of the Lorentz contraction of a rod requires that the rod be the *same* three-dimensional object for all observers in relative motion; this requirement, however, is shown to contradict the relativity of simultaneity.

Two arguments – a formal one (Section 2) and a thought experiment (Section 3) – independently show that the Lorentz contraction of a rod would not be possible if its world path were not a real four-dimensional object. This result provides strong support for the view that Minkowski spacetime represents a four-dimensional reality.

2 FORMAL ARGUMENT

Sometimes special relativity is still regarded as a difficult theory to learn. One of the things that might be contributing to this view is an apparently incorrect Lorentz transformation which is used in the derivation of the Lorentz contraction.

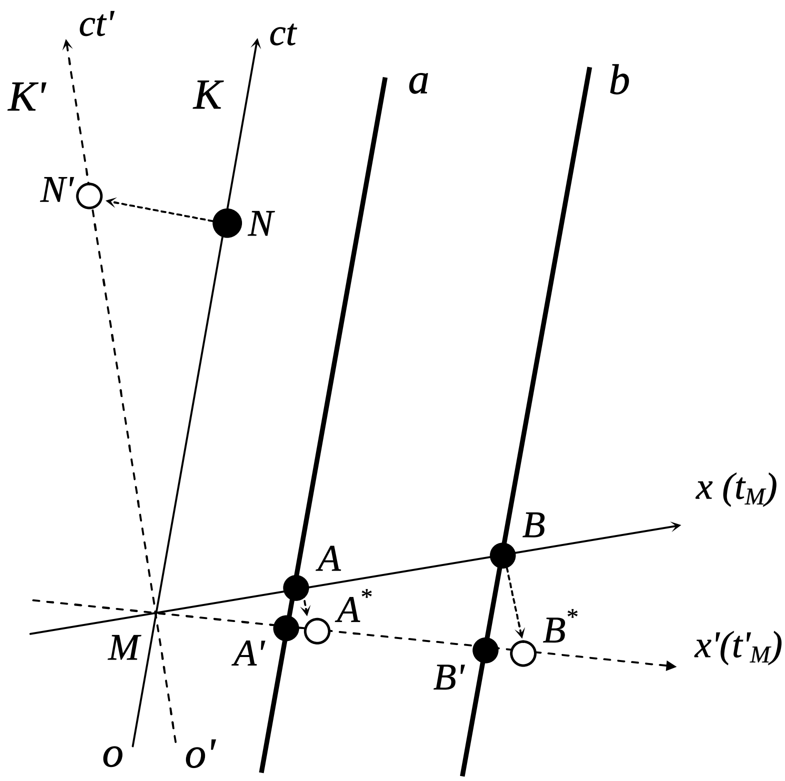

Figure 1

Consider a measuring rod of length $l = (x_B - x_A)$ at rest in a reference frame K which moves relative to another frame K' (Figure 1). Let the events A and B be the rod's end points at the moment $t_M = t_B = t_A$ in K at which the origins of K and K' (represented by the worldlines o and o') coincide at the event M. It appears natural to expect that in order to determine the length l' of the rod in K' we should carry out the Lorentz transformation $K \Rightarrow K'$ which *projects* A and B onto the events A^* and B^* on the x' axis of K'. The reason for this is that we know the coordinates of the end points of the rod in K and want to calculate their coordinates in K' in order to find the rod's length in K'. This transformation gives:

$$l' \equiv \left(x'_{B'} - x'_{A'}\right) = \frac{\left(x_B - x_A\right) + v\left(t_B - t_A\right)}{\sqrt{1 - v^2/c^2}} = \frac{l}{\sqrt{1 - v^2/c^2}}\,, \qquad (1)$$

where $(t_B - t_A) = 0$ since the events A and B are simultaneous in K. However, as seen from (1) what appears to be the correct Lorentz transformation $K \Rightarrow K'$ leads to a wrong physical result – the rod turns out to be longer (not shorter) in K'.

It should be pointed out that the same transformation $K \Rightarrow K'$ is used in the derivation of the time dilation effect and gives the correct physical result (Figure 1): an event N is occurring at the moment t_N in K and the transformation $K \Rightarrow K'$, which projects N onto N', yields the time $t'_{N'} > t_N$ at which N happens in K' (at M $t'_M = t_M = 0$).

The Lorentz contraction is derived by what appears to be an incorrect transformation $K' \Rightarrow K$

$$l \equiv (x_B - x_A) = \frac{(x'_{B'} - x'_{A'}) - v(t'_{B'} - t'_{A'})}{\sqrt{1 - v^2/c^2}} = \frac{l'}{\sqrt{1 - v^2/c^2}},$$

where $t'_{B'} - t'_{A'} = 0$ since the events A' and B' are simultaneous in K'. From here

$$l' = l\sqrt{1 - v^2/c^2}\,. \qquad (2)$$

The reason why the transformation $K' \Rightarrow K$ appears incorrect is the following. Instead of projecting the known coordinates x_A and x_B of the end points of the rod at the moment t_M in K (events A and B) onto the x' axis of K' in order to determine the coordinates of the rod's end points at the moment t'_M in K', we project what we are supposed to determine - $x'_{A'}$ and $x'_{B'}$ at t'_M (the *unknown* events A' and B') – onto the *known* events A and B. The justification for this operation which is given whenever the Lorentz contraction is derived is that the events A' and B' should be simultaneous in K' since the rod's length is determined by measuring its end points at the same time in K'. However, as seen in Figure 1 the events A^* and B^* (obtained by the transformation $K \Rightarrow K'$) are also simultaneous in K'. Therefore the simultaneity requirement is not a justification for and an explanation of the use of the Lorentz transformation $K' \Rightarrow K$.

The reason for employing the transformation $K' \Rightarrow K$ (to obtain the Lorentz contraction) appears to be more profound. In Figure 1 ***a*** and ***b*** are the worldlines of the end points of the rod and its world path is the band formed by ***a*** and ***b***. The instantaneous (three-dimensional) space of K, represented by $x\ (t_M)$, "cuts" the world path of the rod in the "slice" AB. This three-dimensional "slice" represents the rod at t_M in K whose proper length is $l = x_B - x_A$. The instantaneous space of K', represented by $x'(t'_M)$, "cuts" the world path of the rod at a ***different*** angle and the length $l' = x'_{B'} - x'_{A'}$ of the resulting "slice" $A'B'$ is shorter in K'. As seen in Figure 1 the only way the lengths l and l' can be related is by projecting the events A' and B' onto A and B which can be done by the Lorentz transformation $K' \Rightarrow K$.

The fact that not the segment A^*B^*, but the "slice" $A'B'$ gives the correct physical result (2) explains why (2) is obtained by the transformation $K' \Rightarrow K$ – it is this transformation[1] that relates the two pairs of events $A'B'$ and AB. This explanation implies that the world path of the rod in Figure 1 represents a real four-dimensional object whose existence makes it possible for the K- and K'-observers to have ***different*** three-dimensional cross-sections of it. In other words, the two observers have ***different*** three-dimensional objects as measuring rods represented by the cross-sections AB and $A'B'$ in Figure 1 whose lengths are related by the transformation $K' \Rightarrow K$.

[1] The transformation $K \Rightarrow K'$ relates the pairs of events AB and A^*B^* and since the length of the segment A^*B^* is longer than the length of AB the transformation $K \Rightarrow K'$ cannot be used.

If we assume that the world path of the rod is not a real four-dimensional object, then the only real object will be the three-dimensional rod in its rest frame K represented by the "slice" AB. This means that for an observer in K' the rod cannot be a *different* cross-section of its world path. Therefore, there would be no justification for the transformation $K' \Rightarrow K$ since the four-dimensional world path of the rod would not exist and no *different* three-dimensional cross-sections of it whose lengths should be related would be possible. In such a case, as nothing else exists, the *same* "slice" AB of length l would represent the rod for the observers in K and K', the rod would be of the *same* length for both observers and therefore no Lorentz contraction would be possible.

In fact, not only the Lorentz contraction would be impossible if solely three-dimensional objects existed. An existence of three-dimensional objects would imply that reality is a three-dimensional world – the present – and therefore all observers in relative motion would share the same present (as the only reality). And since the present is defined as the class of simultaneous events at the present moment that class will be common to all observers which means that simultaneity turns out to be absolute. In general, if it is assumed that reality is a three-dimensional world, immediate contradictions with all kinematic consequences of relativity are reached (Petkov [1986]).

As the rod that exists for the K'-observer at the moment t'_M is *not* the *same* three-dimensional rod that exists for the K-observer at t_M, the K'-observer's rod is not a deformation of the K-observer's rod (a deformation hypothesis implies that the same three-dimensional rod undergoes contraction for the K'-observer). Therefore, the existence of two different three-dimensional objects for the K- and K'-observers makes it clear that no forces are involved in the Lorentz contraction. Simply, the K'-observer's rod is a three-dimensional "slice" of the rod's world path, which is different from the K-observer's "slice" and turns out to be shorter.

3 THOUGHT EXPERIMENT

The physical meaning of the Lorentz contraction can be made even clearer by the following thought experiment (Figure 2). Consider again a measuring rod at rest in the reference frame K. Its end points are represented by the worldlines a and b and its middle point coincides with the origin of K depicted by the worldline o. There are lights incorporated at the end and middle points of the rod. Every instant the color of the lights changes *simultaneously* in K: at the moment t_g all three lights are green, at t_r the lights are red, and at t_b they are blue.

A reference frame K' moves relative to K and its origin, represented by the worldline o', coincides with the origin of K at the event M – the intersection point of the worldlines o and o'. The meeting happens at t'_M of K' time and at $t_M = t_r$ of K time. At the instant of the meeting all lights of the rod are red as determined in K. Therefore at that moment what exists for an observer in K is the red rod – the three red lights are simultaneous for the K-observer at his present moment $t_M = t_r$. The green rod existed for the K-observer one instant before the meeting and is in his past while the blue rod will exist one instant after the meeting and is in his future. The green and blue rods do not exist for the *K*-observer at $t_M = t_r$ if one insists that only present objects exist[2].

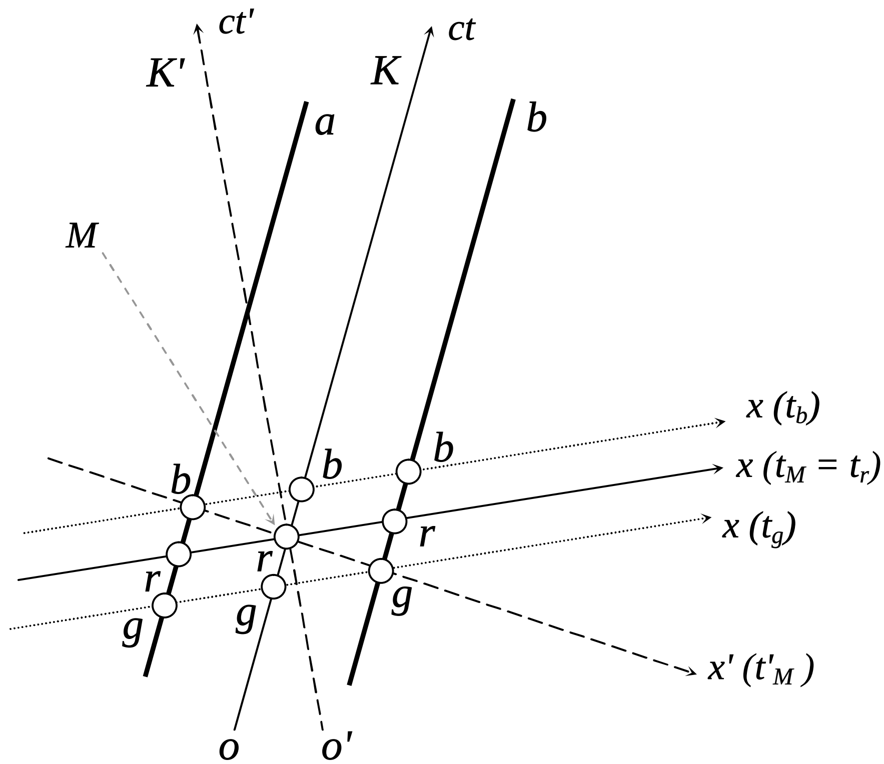

Figure 2

As an observer in *K′* has a different class of simultaneous events, at the moment of the meeting t'_M the lights of the rod will not be all red for the *K′*-observer. He will determine that the rod's front end point, middle point, and rear end point will be green, red, and blue, respectively (*K′* is moving to the left in Figure 2). This means that the green-red-blue rod, which is present for *K′* consists of part of the rod that existed in the *K*-observer's past (the front end point with green light), the middle part of the rod (which is also present and therefore existing for the *K*-observer at the moment of the meeting $t_M = t_r$), and part of the rod that will exist in the *K*-observer's future (the rear end point with blue light). As all parts of a three-dimensional object exist *simultaneously* at the present moment of an observer the three-dimensional rod that exists for the *K′*-observer at his present moment t'_M is *different* from the three-dimensional rod of the *K*-observer existing at his present moment $t_M = t_r$ (the event of the meeting *M* in Figure 2 is the only common present event for both observers).

[2] The best way to demonstrate the irrelevance of a language argument – the green rod existed and the blue rod will exist – is to state explicitly what the dimensionality of the measuring rod is. If the rod is a three-dimensional object, it exists only at the present moment (see below). The past of the rod is the set of its previous *states*; its future is the set of its forthcoming *states*. Therefore, the rod's past and future do not exist in any way since they are only *states* of the rod which exists as a three-dimensional object solely at the moment "now". The Lorentz contraction has a meaning if the pre-relativistic division of events into past, present and future is used since only this division makes it possible for the rod to be a three-dimensional object (see below).

The rod of each observer is composed of a mixture of parts of the past, present, and future rods of the other observer.

As existence is absolute[3] what exists for the *K′*-observer must exist for the *K*-observer as well. Therefore, the past green rod and the future blue rod are not just states of the present red rod for the *K*-observer (as the three-dimensional view of reality requires), but are as real as the present red rod. For this to be possible, however, the world path of the rod must be a real four-dimensional object. Only in this case the instantaneous three-dimensional spaces of *K* and *K′*, represented in Figure 2 by the lines $x\ (t_M = t_r)$ and $x'(t'_M)$, respectively, can "cut" two ***different*** three-dimensional "slices" from the rod's world path – the red "slice" represents the present rod for the *K*-observer at $t_M = t_r$, while the ***shorter*** green-red-blue "slice" is interpreted by the *K′*-observer as a relativistically contracted rod which exists at t'_M as his present rod.

The present analysis shows that what is depicted in Figure 2 is not merely a convenient abstract construct representing the Lorentz contraction. The very existence of the Lorentz contraction demonstrates that the measuring rod must be a four-dimensional object in order that two observers in relative motion have different three-dimensional rods which are cross-sections of the rod's world path. Since this is a strong claim let me consider three possible objections to the analysis which this claim is based on.

One might argue that the contracted rod in *K′* should not be regarded as a three-dimensional "slice" of a real four-dimensional world path which is ***different*** from the "slice" representing the rod in its rest frame *K*, but as a deformation of the ***same*** three-dimensional object – the ordinary rod of our everyday experience. Leaving aside all problems such a proposal encounters I will point out one immediate contradiction with relativity. If the ***same*** three-dimensional object (say the red rod) is all that exists for the observers in *K* and *K′*, no relativity of simultaneity is possible – the rod's front end, middle, and rear end points with red lights on will exist simultaneously for ***both*** *K*- and *K′*-observers. This contradiction again demonstrates that no forces[4] are involved in the explanation of the Lorentz contraction since the contracted three-dimensional rod that exists for the *K′*-observer at his present

[3] In order to preserve a version of the ordinary view of reality as an evolving in time three-dimensional world it is tempting to assume that special relativity relativized existence as well. Although it is unlikely that anyone would support the relativization of existence, in another paper I will show that a relativized existence contradicts special relativity itself; more specifically it contradicts the twin paradox effect.

[4] There still exist views that the possibility of a force explanation of the length contraction cannot be ruled out. I will mention J. Bell (1987) mostly due to his thought experiment designed to demonstrate that the length contraction involves deformation forces. In this experiment spaceships *B* and *C* which are connected with a fragile thread accelerate gently in such a way that at every moment they have the same velocity relative to an inertial spaceship *A*, "and so remain displaced one from the other by a fixed distance". Bell claims that as the spaceships *B* and *C* speed up the thread "will become too short, because of its need to Fitzgerald contract, and must finally break. It must break when, at a sufficiently high velocity, the artificial prevention of the natural contraction imposes intolerable stress". An immediate problem with Bell's claim is his assumption that the ***space*** between *B* and *C* does ***not*** contract whereas the thread does. Also, as a rule those who believe the length contraction involves forces do not analyze sufficiently the reciprocity of this effect. Had Bell considered that it was spaceship *A* that slowly increased its velocity while *B* and *C* moved with constant velocity he would have realized that the distance between *B* and *C* would have also shortened as determined by *A* and the thread would have remained intact (it should be noted that acceleration is absolute, but in Bell's experiment its sole role is to ensure a continued increase of the length contraction). Thus taking the reciprocity of the effect into account demonstrates that the thread cannot break due to its Lorentz contraction.

moment t'_M is *not* the *same* three-dimensional rod which exists for the K-observer at his present moment $t_M = t_r$. The instantaneous space of the reference frame in which the rod is at rest "cuts" the longest "slice" from the rod's world path whereas the "slices" that are "cut" by the instantaneous spaces of the frames moving relative to the rod's rest frame are shorter.

It should be emphasized that it is meaningless to talk about the *same* three-dimensional object in special relativity. As an *extended* three-dimensional object (a measuring rod, for example) is defined as an object whose parts exist *simultaneously* it follows from the relativity of simultaneity that observers in relative motion have *different* three-dimensional objects which are non-coinciding three-dimensional cross-sections of the world path of the rod. Precisely for the same reason two observers in relative motion have different three-dimensional spaces which are different three-dimensional "slices" of spacetime.

One might also object to this analysis of the Lorentz contraction by pointing out that the argument used here to demonstrate the reality of the rod's world path is essentially the Rietdijk-Putnam argument (Rietdijk [1966], Putnam [1967]). Stein's objection to that argument is well-known (Stein [1968], [1991]). In this case it states that all three parts of the rod with red lights on cannot experience the same present since "in the theory of relativity the only reasonable notion of 'present *to a space-time point'* is that of the mere identity relation: present to a given point is that point alone – *literally* 'here-now'" (Stein [1991 p. 159]). So, according to Stein, when the observers located at the origins of K and K' meet at event M the only real (present) event for them is M itself. In other words, the only real "object" for them will be the middle point of the rod with the red light on and nothing else. Therefore neither of the observers will be able to regard the *extended* rod as existing. To deny the reality of the *whole* rod which is being measured by observers in K and K' seems unrealistic.

As an appeal to realism is not a strong argument it can be shown that if the Rietdijk-Putnam argument is generalized, Stein's objection does not hold. That generalization naturally follows if the issue of the ontological status of Minkowski spacetime is explicitly addressed (Petkov [1986]). Assuming dimensionality is an ontological feature of reality the question "What is the dimensionality of reality according to special relativity?" has three possible answers: (i) three-dimensional (our ordinary three-dimensional world evolving in time), (ii) three-dimensional but observer- or frame-dependent (in this case existence is relativized), and (iii) four-dimensional (represented by Minkowski spacetime).

As "[t]he concept of existence … cannot be relativized without destroying its meaning completely" (Gödel [1949, p. 558]) option (ii) does not appear to have any chances of providing an acceptable answer to the above question (see the footnote on p. 5). Option (iii) is obviously what this paper is trying to prove. Only option (i) needs a closer look. It directly leads to a generalization of the Rietdijk-Putnam argument when relativity of simultaneity is taken into account. As a three-dimensional world (the present) is the class of events occurring *simultaneously* at the moment "now" two observers in relative motion, having different classes of simultaneous events at their "now" moments, will have different three-dimensional worlds (different presents). As seen in Figure 2 part of the present of the observer in K, represented by the line x $(t_M = t_r)$, lies in the K' -observer's future and part in the K' -observer's past. Therefore, as existence is absolute both observers' presents should exist for both of them which is possible if reality is four-dimensional. Otherwise, if reality were a three-dimensional world, as the only existing it would be common to all observers in relative motion which would mean that all observers would have a common class of simultaneous events; thus simultaneity would be absolute.

If the issue of dimensionality is explicitly addressed, Stein's objection does not hold since his insistence that every observer should regard only one event (here-now) as present (i.e. real) does not constitute a clear position on what the dimensionality of reality is; obviously what is real for an observer cannot be reduced to a single event.

Stein's objection needs further analysis since it is based on an apparently valid argument – that the division of events into past, present, and future used by Rietdijk and Putnam is pre-relativistic. The question of division of events should be cleared up since it is a continued source of confusion. On the one hand, those who reject the reality of all events of spacetime (the block universe view) explicitly or implicitly claim that reality is a three-dimensional world evolving in time. On the other hand, however, they accept the relativistic division of events according to which past and future events with respect to an event, say event *M* (Figure 3), are the events lying in the past and future light cones of *M*, respectively, while the events occupying the region "elsewhere" located outside of the light cone do not have a clear status and sometimes are regarded as a relativistic generalization of the classical class of present events.

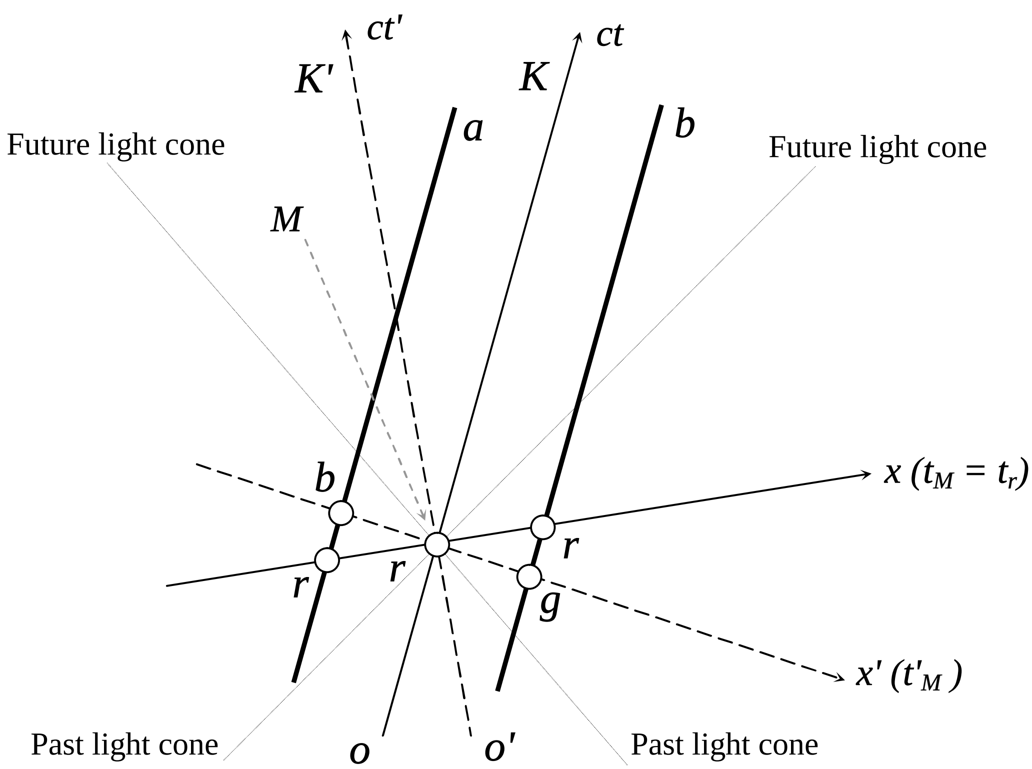

Figure 3

The view that reality is a three-dimensional world is clearly incompatible with the relativistic division of events. A three-dimensional world necessarily requires a *pre-relativistic* division of events since it is defined as the class of *simultaneous* events at the present moment (as all three-dimensional objects, field and space points existing simultaneously at the moment “now”) or, by exclusion, as all events that are *not* past and future. As seen in Figure 3 if reality is defined in terms of the relativistically determined past, present and future events, it is not a three-dimensional world, but a four-dimensional region of spacetime – the region elsewhere outside of the light cone which excludes the relativistically determined past and future events. If the elsewhere region is regarded as what is real, then the ***K***- and ***K'***-observers at ***M*** will have a *common* reality (which is *not* three-dimensional). However, that is true only at the instant they meet. After they separate the elsewhere region of each observer will contain parts of the past and future cones of the other observer. Therefore the conclusion that all events of spacetime are real is inevitable.

Now, I believe, it becomes evident that the Rietdijk-Putnam argument has never been seriously challenged. Even what appears to be a valid argument against it – that it uses the pre-relativistic division of events – is not an argument at all. Rietdijk and Putnam used that division since it preserves the three-dimensionality of the world. The essence of their argument is that the ordinary three-dimensional view of reality (based on the pre-relativistic division of events) inevitably leads to the view that reality is a four-dimensional world if relativity of simultaneity is taken into account. Had the critics of the Rietdijk-Putnam argument applied the relativistic division of events and addressed the dimensionality issue they themselves would have reached Rietdijk’s and Putnam’s conclusions (as shown in the preceding paragraph).

It should be stressed that the Lorentz contraction is meaningful if every observer regards the measuring rod as a *three*-dimensional object which, due to the relativity of simultaneity, is *different* for observers in relative motion. At the present moment of an observer, when it is measured, the rod is obviously a *present* three-dimensional object for that observer – for the ***K***-observer his present rod is the three-dimensional “slice” that is “cut” by his instantaneous space $x\ (t_M = t_r)$ while for the ***K'***-observer his present rod is the “slice” his instantaneous space $x'(t'_M)$ “cuts” from the world path of the rod. However, as seen in Figure 3 those three-dimensional “slices” result from a *pre-relativistic* division of the spacetime events (by the ***K***- and ***K'***-observers) into past, present, and future ones. If one uses the relativistic division then the elsewhere region (containing the relativistically present events) “cuts” from the world path of the rod *not* a three-dimensional “slice”, but a four-dimensional object which is the same for both observers in relative motion at the event ***M*** and therefore there is no Lorentz contraction. Thus a *relativistic* effect – the length contraction – makes sense if each of two observers in relative motion applies a *pre-relativistic* division of events since it is this division which ensures that the rod for every observer is *three*-dimensional and existing at his present moment.

In fact, both relativity of simultaneity and time dilation make sense in terms of the pre-relativistic division of events (used by observers in relative motion) if the observers are asked to state what the dimensionality of reality is. If each of them considers reality to be three-dimensional[5] (the class of events that are simultaneous at his present moment), then all observers in relative motion have different classes of simultaneous events at their present

[5] It should be emphasized again that only the pre-relativistic division of events produces a class of simultaneous events that form a three-dimensional world. As seen in Figure 3 the relativistic division does not yield a three-dimensional world. That is why, I believe, the question of dimensionality of reality should be addressed in any analysis of the philosophical implications of relativity.

moments and therefore different three-dimensional worlds (which ultimately leads to the view that reality is four-dimensional as existence is absolute); time dilation is a direct consequence of relativity of simultaneity. If the observers regard reality as a four-dimensional world, all spacetime events are real and therefore one cannot define a class of simultaneous events that is objectively privileged (different) with respect to the other events of spacetime.

A third objection against the present analysis might point out that due to the conventionality of simultaneity both observers (in K and K') at event M are free to choose their instantaneous spaces from the spacetime region outside of the light cone of M. However, this is not a real objection since it implies what is argued for in this paper – that reality at the macroscopic level is four-dimensional. Indeed, due to the conventionality of simultaneity all events outside of the lightcone of an event exist which leads to the view that all events of spacetime are real (Weingard [1972]). In fact, the profound meaning of the conventionality of simultaneity (and of the logical circle reached when one tries to determine the one-way velocity of light) is that reality is a four-dimensional world whose mathematical model is Minkowski spacetime (Petkov [1989]): as all events of spacetime exist it is really a matter of convention which class of events lying outside of the lightcone of an event will be considered simultaneous; this means that since an observer is free to choose his instantaneous space from the region outside of the light cone the back and forth velocities of light will obviously depend on that choice.

4 CONCLUSIONS

The analysis of the Lorentz contraction of a rod carried out in this paper shows that (i) the rod's world path must be a real four-dimensional object in order that the Lorentz contraction be possible, and (ii) no forces are involved in this relativistic effect. The requirement that a rod's world path must be real has a direct implication for the issue of the dimensionality of reality according to special relativity – reality is a four-dimensional world represented by Minkowski spacetime. This result appears to rule out the existence of objective becoming in the framework of relativity despite recent attempts in that direction - see (Clifton and Hogarth [1995]), for instance.

The present analysis also holds when general relativity is considered since the Lorentz contraction is present in that theory as well. The only difference is that in general relativity reality is represented by a *curved* spacetime.

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