Relativistic Thermodynamics and the Passage of Time*

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ABSTRACT

The debate about the passage of time is usually confined to Minkowski's geometric interpretation of space-time. It infers the block universe from the notion of relative simultaneity. But there are alternative interpretations of space-time – so-called axiomatic approaches –, based on the existence of 'optical facts', which have thermodynamic properties. It may therefore be interesting to approach the afore-mentioned debate from the point of view of relativistic thermodynamics, in which invariant parameters exist, which may serve to indicate the passage of time. Of particular interest is the use of entropic clocks, gas clocks and statistical thermometers, which suggest that two observers in Minkowski space-time could agree on an objective passing of time.

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1. Introduction

The long running debate about the block universe, taken to be a conceptual consequence of the Special theory of relativity, usually relies on the discovery of relative simultaneity for support. As mechanical clocks run differently in reference frames, moving inertially with respect to each other, the relativity of simultaneity implies that there can be no universal Now in Minkowski space-time. Hence the passage of time must be a human construction, in the Kantian sense, whilst the physical universe is taken to be a four-dimensional block. Gödel (1949) argued that the relativity theory provided 'proof' of the idealist view of time, due to the relativity of simultaneity, which implies that the

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temporal succession of events loses its objective status. Those who argue against the block universe, as a conceptual consequence of the Special theory, usually point out that the space-time interval, *ds*, is invariant for all observers, who consider time-like related events (Capek 1966, 1983). The invariance of the line element, *ds*, implies that the order of time-like related events is the same for all observers, even though they cannot agree on the simultaneity of these events. This debate is usually confined to considerations of the geometric structure of Minkowski space-time. Only Einstein, in his reply to Gödel, brought thermodynamics into the debate. In characteristic style, Einstein resorted to a thought experiment. An electromagnetic signal is sent, within a light cone, from a past source, A, to a future receiver, B, through a present point, P. Einstein concludes that the sequence of events is irreversible, since the emission of the signal happens before its reception at B. This secures the «one-sided (asymmetric) character of time [...], i.e., there exists no free choice for the direction of the arrow» (Einstein 1949, p. 687). Following Planck, Einstein (1907) had established early in his career that entropy is frame-invariant. Einstein's appeal to thermodynamics raises the question whether relativistic thermodynamics offers invariant relationships, in addition to *ds*, which would allow us to avoid Gödel's conclusion.

The purpose of this paper is to consider whether it is possible to build a thermodynamic clock, based on considerations of invariants in relativistic thermodynamics, which would lead to a frame-invariant reading of time for two observers who move inertially with respect to each other at relativistically significant velocities. If such invariant relationships could be found, they may be more appropriate for a discussion of the passage of time in Minkowski space-time. The space-time interval *ds* is merely a geometric measure in Minkowski space-time, whilst thermodynamic properties of signal propagation are physical in nature, a fact to which Einstein alluded in his thought experiment. The question of temporal becoming in relation to relativistic thermodynamics has, according to the author's knowledge, not yet been considered in the literature but it may throw new lights on an old debate.

2. Lorentz-invariant parameters

In a thermodynamic system, moving with velocity, v, several thermodynamic parameters remain invariant. According to Max Planck (1907), the following invariant relationships hold in relativistic thermodynamics:

$$p = p_o, n = n_o, S = S_o.$$

Of particular interest is the Lorentz invariance of entropy, *S*, which can easily be established by recalling the definition of entropy in statistical mechanics: $S = k \log N$. The number of microscopic states, *N*, which correspond to a given macrostate does not depend on the velocity of the thermodynamic system, so that $S = S_o$. According to this equation two observers in inertially moving systems would agree on a change in entropy of a system under observation. Could the invariance of entropy serve to measure the passage of time, objectively? In considering this question it is useful to recall that mechanical clocks are not necessarily needed to measure time. Galileo used simple water clocks in his fall experiments to establish that distance, *d*, is proportional to time squared, t^2. The frame invariance of entropy means that in both systems, moving inertially with respect to each other, the entropy of a body in thermodynamic equilibrium is constant and is not dependent on the velocity of the body (Møller 1972, p. 237). The same conclusion holds for increases in entropy, δS, for systems in relative motion (Schlegel 1968, p. 148). Whether the invariance of a change in entropy of a body as measured in two different reference systems could serve two observers as a basis for the measurement of time depends on whether we consider entropy is defined in classical thermodynamics or statistical mechanics. Imagine that two observers agree to perform an experiment: observer A sits on a train, which moves at relativistic speeds and observer B sits on the platform. Let the experiment simply consist in computing the change of entropy when an ice cube is put into a container with warm water. Let's say that the two observers agree to perform a certain act when the ice cube has melted – but they would have to agree on the moment when they begin the experiment, for which they would need a clock. But mechanical clocks are not frame-invariant. Furthermore the change in entropy for such a system is defined, in classical thermodynamics, as

$$\Delta S = \int \frac{dQ}{T}$$

but have they established that the temperature, T, is frame-invariant?

Unfortunately, there is no agreement amongst physicists as to whether temperature is Lorentz invariant. According to the classic papers by Planck and Einstein, the proper transformation for temperature is:

$$T = \beta T_0, \text{where } \beta = \sqrt{1 - {v^2}/{c^2}},$$

with the consequence that a moving body would appear cooler (Pauli 1981, §.46). Whilst this view was generally accepted, it has also been proposed that $T = T_0/\beta$, with the consequence that a moving body would appear hotter.[1] In either case temperature suffers a dilation or contraction effect in the moving system, similar to the well-known relativistic effects. Such relativistic effects seem to rule out an invariant clock reading across two inertial systems. But does this mean that two observers should conclude that time is a human illusion? Many authors jump to this conclusion:

> Due to the absence of an observer-independent simultaneity relation, Special relativity does not support the view that 'the world evolves in time'. Time, in the sense of an all-pervading 'now' does not exist. The four-dimensional world simply is, it does not evolve. (Ehlers 1997, p. 198)

> Each observer has his own set of nows and none of the various systems of layers can claim the prerogative of representing the objective lapse of time. (Gödel 1949, p. 558)

It has not been sufficiently appreciated that the situation, to which the authors appeal, is not essentially different from many other situations, in which two different observers need to adopt transformation rules to calculate their respective perspectival observations. Consider, for instance, how two famous Greeks, Eratosthenes (276-196 BC), located in Syene, and Archimedes (287-212 BC), located in Alexandria, would determine midday in their respective locations. They would use sundials but the distance between the two locations means that they would not agree on when midday occurs. Nevertheless, they could use some elementary facts to determine midday in each other's location. When the sun is at its highest point in Syene, it throws a shadow of $7^{\circ}12'$ in Alexandria, which is approximately 800km to the west of Syene. As the Greeks knew the rotational speed of the sun around the Earth (on the geocentric model of the universe) Archimedes and Eratosthenes could calculate midday in each other's location, using appropriate transformation rules. In order to do so, it is essential that the motion of the sun across the sky is both regular and invariant for the two observers. As this was the case they had no reason to conclude that midday is an illusion.

[1] See McCrea 1935, §.54; Perrot 1998, p. 264; Dunkel and Hänggi 2009.

For the modern physicist the transformation rules are provided by the Lorentz transformations for the time coordinates:

$$t' = \frac{t - \left(v/_{c^2}\right)x}{\sqrt{1 - v^2/_{c^2}}}$$

which indicates the time dilation in moving clocks:

$$t' = \frac{t}{\sqrt{1 - v^2/_{c^2}}}.$$

It is not obvious why the observers should conclude that the passage of time is a human illusion, as it is often claimed. The Lorentz transformations are perfectly invariant and do not depend on the reference frame of the observer. However, for the two observers to calculate their respective clock times, they must know the velocity of their respective frames, just like Archimedes and Eratosthenes must know the distance between their respective locations and the velocity of the sun's motion. The need to know the velocities of the respective systems so that some transformation rule can be applied leaves a loophole in the argument. If the observer A does not know the velocity of B then the clocks tick differently for them but they cannot calculate each other's clock times. In this case time and its passage seem to be truly relative.

3. Geometric and Thermal Time

It is therefore worth investigating whether there are invariant relationships in the Special theory, which could serve as a common basis for time. It is customary for defenders of temporal becoming to point to the existence of the so-called space-time interval, ds, ($ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2$), according to which the space-time length between two observers, moving inertially with respect to each other, is invariant ($ds = ds'$), whilst their clock readings are subject to time-dilation effects, and relative simultaneity (Capek 1966, 1983, Nehrlich 1982). However, the space-time interval ds, although invariant, is ill-suited for the measurement of time, because it measures the space-time length between two events and lets the temporal parameters vary according to the reference frame.

The velocity of light is also an invariant in Minkowski space-time. However, we should note a systematic ambiguity in the treatment of *c*. In the standard *geometric* interpretation of Minkowski space-time, *c* is not a physical signal, which propagates through space-time at a constant velocity (approximately $3x10^8 \, {}^{m}\!/_{s}$). Rather, *c* constitutes a geometric limit of the light cones – sometimes taken to represent the causal structure of Minkowski space-time – such that no subluminal particles, which trace their world lines through space-time, are permitted to reach this limit because of the effect of relativistic mass:

$$m = \frac{m_0}{\sqrt{1 - {}^{v^2}\!/_{c^2}}}.$$

According to this geometric representation of Minkowski space-time, time stands still for light signals, *c*, which constitute the causal boundaries of the light cones in Minkowski space-time. On the standard geometric interpretation this reduces the measurement of time to the frame-dependent behaviour of mechanical clocks. It is *geometric* time.

Einstein hints at an alternative reading of *c*: it is also a physical signal, which propagates at a constant speed between two events in space-time. Although Minkowski's geometric approach is the predominant view today, alternative approaches were developed soon after the publication of the Special theory of relativity.[2] They are based on the propagation of light signals in space-time. As Einstein indicates, on these so-called axiomatic approaches, thermodynamic aspects of optical facts have to be taken into account. These axiomatic attempts reverse the usual tendency to 'spatialize time'. For instance, Robb starts with the thesis that 'spacial relations' may be analyzed in terms of the time relations 'before' and 'after' or, as he concludes, «that the theory of space is really a part of the theory of time» (Robb 1914, Conclusion). Essential for this conception is the notion of conical order, which is analyzed in terms of the relations of 'before' and 'after' instants of time. An instant (an element of time) is the fundamental concept, rather than the space-time event. Furthermore the

[2] See Robb 1914, Cunningham 1915, Carathéodory 1924, Schlick 1917, Reichenbach 1924.

'before/after' relation of two instants is an asymmetrical relation. In this way Robb builds a system of geometry, in which we encounter the familiar light cones of the Minkowski representation of space-time. Robb reverses the Minkowski approach in terms of geometrical relations and starts from physical facts, an approach, which is reflected in Einstein's later reservations about the block universe.

> If a flash of light is sent out from a particle P at A1, arriving directly at particle Q at A2, then the instant A2 lies in the α-subset of instant A1, while the instant A1 lies in the ß-subset of A2. Such a system of geometry will ultimately assume a four-dimensional character or any element of it is determined by four coordinates. [...] It appears that the theory of space becomes absorbed in the theory of time. (Robb 1914, pp. 8-9)

Here the α-subset is the future light cone of instant A1 and the ß-subset is the past light cone of A2. (Figure I)

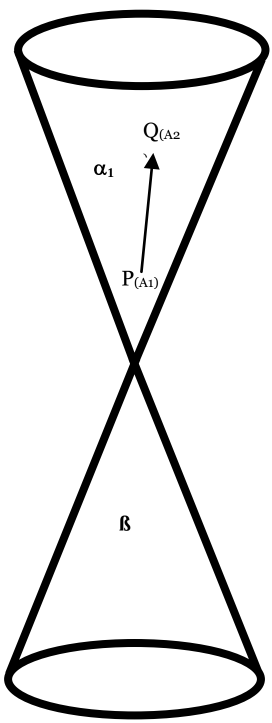

Figure I: 'Corresponding to any point in space, there is an α-cone of the set having that point as vertex, similarly there is also a ß-cone of the set having the point as vertex.
If A_1 be any point and α_1 the corresponding α-cone, then any point A_2 is after A_1, provided $A_1 \neq A_2$ and A_2 lies either on or inside the cone α_1.

(Robb 1914, 5-6)

The axiomatic approaches raise the question of frame-invariant thermodynamic properties.

The propagation of *c* between space-time events has certain limitations for the measurement of time. Whilst the velocity of light is the same for all observers in Minkowski space-time, the direction of a light ray depends on the relative angle between the frame and the light source. This phenomenon is known as aberration. (Giulini 2005, §.3.6) Furthermore if the two observers exchange light signals between each other they will be subject to the relativistic Doppler effect, which affects the frequency, ν, and wavelength, λ, of the signal, respectively.

Taking these relationships into account, observers can still calculate each other's signal properties. For instance, the twins in the famous twin paradox use light signals as light clocks but as before, the Earth-bound twin needs to know the velocity of the space ship of his twin brother. He is then able to make corrections, which will allow him to compute how much time has elapsed for this brother. The brothers can even send regular signals to each other and using the formulae for the relativistic Doppler Effect, they can calculate how many signals will arrive at each end. Once again, on the basis of these calculations, the twins have no reason to conclude that time is an illusion.

Are there any other invariant relationships, which could be used for this purpose? It is at this point that we should turn to relativistic thermodynamics, for it offers a number of invariant relationships, which may be useful to two observers moving inertially with respect to each other. If we free ourselves from the assumption that time must be measured by mechanical clocks, which are subject to relativistic effects, then it is possible to conceive of other ways of measuring time. As mentioned above, Galileo did not use mechanical clocks to measure time in his inclined plane experiments but used water clocks, i.e., he measured the passage of time of the ball down the plane by the flow of water from a bucket and then weighed the amount of water collected. Is it, for instance, conceivable to build a gas clock, which uses the invariance of p? Such a clock could be made of «two chambers with a small connecting tube through which gas can leak from one chamber to the other» (Schlegel 1968, p. 137). Observers in relativistically moving systems know the pressure is invariant (where pressure is force per unit area), so that the relationship $p = p_0$ could be used to coordinate activities in relativistically moving systems. For instance, when the pressure is the same in both systems, the two observers can perform certain actions simultaneously. Invariance means that two such gas clocks have the same rate both at rest and «when in uniform motion relative to each other» (Schlegel 1968, p. 137). This requires of course that the two gas clocks are in the same state and that the beginning of the experiment in the two inertial systems can be coordinated in a Lorentz-invariant manner, like the exchange of light signals.

In a similar manner we can return to the Lorentz-invariance of entropy in statistical mechanics. As the entropy increases in the two clocks, attached to two inertial systems in relative motion with respect to each other, is invariant, we must conclude that two such «entropy clocks, in relative uniform motion, will run at the same rate» (Schlegel 1968, p. 148). The invariance of entropy and pressure could therefore serve both to measure the passage of time (by appropriate period units) and to coordinate events in relativistically moving systems. Note that these parameters do not require knowledge of the relative velocities of the systems involved. What about temperature? We have reason to reconsider temperature, since according to Landsberg, there is no experimental confirmation of the relationship $T = \beta T_o$ and it has to be taken into account that temperature is a statistical concept (Landsberg 1966, p. 571).

Of particular interest is the question whether a thermodynamic thermometer could be built, which would indicate the passage of time for two observers, attached to different reference frames. The possibility of such a Lorentz-invariant thermodynamic clock, in which the notion of temperature plays a significant part, is based on the work of P. T. Landsberg. In a series of publications, Landsberg (1966, 1967, 1978) critically discussed the prevailing view, mentioned above, that temperature is not Lorentz-invariant in relativistic thermodynamics. The crucial idea that the passage of time must be linked to physical phenomena, in particular thermodynamic phenomena, motivates much of the research in the area of the emergence of time from fundamental symmetry. It gives us a notion of *thermal* time:

> [...] it is the statistical state that determines which variable is physical time, and not any a priori hypothetical "flow" that drives the system to a preferred statistical state. When we say that a certain variable is "the time", we are not making a statement concerning the fundamental mechanical structure of reality. Rather, we are making a statement about the statistical distribution we use to describe the macroscopic properties of the system that we describe macroscopically. The "thermal time hypothesis" is the ideal that what we call "time" is the thermal time of the statistical state in which the world happens to

be, when described in terms of the macroscopic parameters we have chosen. (Rovelli 2008, p. 8)

Landsberg's hypothesis about the invariance of temperature has recently received renewed attention, because of the importance of a relativistic equilibrium velocity distribution in the description of several high-energy and astrophysical events (Chacón-Acosta et al. 2009, Bíró and Ván 2010).

4. LORENTZ-INVARIANT TEMPERATURE

Going against the established views, Landsberg[3] argues that temperature is invariant ($T_o = T$) and some recent theoretical results and computer simulations seem to confirm this view. To develop the argument, Landsberg assumes a transformation law $T = \gamma^a T_o$, according to which a body μ has temperature T_o in an inertial rest frame, I_o, and an identical body ν has temperature $\gamma^a T_o$ in a moving inertial frame, I. If these bodies are allowed to interact, one expects heat flows between them. If that is the case, then observers in the respective frames will see the other body as hotter if a>0, and cooler if a<0, respectively. For instance, if a<0, then in μ's rest frame, μ's temperature should increase at the expense of ν's temperature (Landsberg 1978, p. 348). In μ's rest frame, this heat flow would take the form:

$$T_{\mu_o} \uparrow, T_{\nu_o} \downarrow$$

and in ν's rest frame, by the principle of relativity, it would take the form:

$$T_{\nu_o} \uparrow, T_{\mu_o} \downarrow .$$

The reason for this inconsistency is that, according to the Second law of thermodynamics, heat flows are involved when two bodies are brought into thermal contact, whereas no heat flows occur between moving clocks. In order to avoid the inconsistency, Landsberg sets a=0, so that $T=T_o$. If this argument

[3] Landsberg 1978, ch. 18.5; Landsberg 1966, 1968; cf. C. Møller (1972, p. 233). In other, more recent approaches, temperature has been used to connect geometric and thermal time: «We now interpret temperature as the ratio between the thermal time and the geometrical time, namely $t = \beta\tau'$. Temperature is $T = {}^{1}/_{k_b \beta}$». Whilst the thermal time flow is state-dependent, the authors also consider a state-independent notion of time flow (Connes and Rovelli 1994, pp. 20-21).

is correct then it should be possible in principle to construct a thermodynamic clock, in which the temperature remains invariant since it is unaffected by the relativistic motion of bodies. Then a thermostat, on Landsberg's hypothesis, would read identical temperatures and temperature readings could be used as primitive clocks. Then, if certain conditions are satisfied, the rise of the temperature in the test bodies, μ placed in the system at rest and ν in the system in motion, could be used to measure the passage of time. Equally, when the two bodies, μ and ν, reach the same temperature in the two inertially moving systems, the observers could perform some prearranged action simultaneously. If temperature is indeed Lorentz-invariant, they would know that they perform their actions simultaneously. Of course the thermostats have to be coordinated at the beginning of the experiment.

As mentioned above no agreement has been reached about the existence of a Lorentz-invariant temperature. The problem is that none of the formulations proposed are covariant and in order to proceed we need a generalized equipartition theorem. (Landsberg 1967, p. 904) Recent work has emphasized that the different relativitistic temperature concepts are based on different assumptions about thermodynamic quantities, like heat, energy transfer etc., which lead to different transformation rules for temperature. One way to identify these assumptions is to consider from which hyperplane in Minkowski space-time thermodynamic parameters are defined (Dunkel and Hänggi 2009; Bíró and Ván 2010). As this procedure gives rise to different ways of identifying thermodynamic quantities with statistical averages, it is desirable to obtain a covariant formulation of the equipartition theorem and the Jüttner distribution – the relativistic generalization of the Maxwell distribution.

The aim of such a covariant formulation is to show how an invariant temperature can be derived from it, thus avoiding the question of which Lorentz transformation to adopt for temperature. Mathematically this procedure involves the use of four vectors, in terms of which the invariant temperature is defined (Chacón-Acosta et al. 2009; Bíró and Ván 2010).

What makes this work interesting is that recent computer simulations are seen as an experimental confirmation of Landsberg's hypothesis (Cubero et al. 2007). Temperature, according to these findings, can be measured in a frame-independent way. Thus moving bodies appear neither cooler nor hotter, offering the possibility of constructing a thermodynamic clock, which would tick at the same rate for all inertial observers. The authors first experimentally confirm that the correct generalization of the Maxwell velocity distribution in

Special relativity is the Jüttner distribution (1911). The Jüttner distribution revises the Maxwell distribution function to accommodate upper bounds on the velocity of atoms. It also yields a well-defined concept of temperature in Special relativity. As Landsberg had already indicated when two systems are brought into contact they approach a 'thermodynamic equilibrium state'; each subsystem is described by the same velocity distribution function $f_j(v, m_j, \beta)$ and they only differ in their rest masses but share the distribution parameter β_j, which is determined from the initial energy. This parameter, which already appears in the Maxwell distribution function $\left(\beta = {}^{T}/_{k_b}\right)$can then be used to 'define a relativistic equilibrium temperature $(T = k_b\beta)^{-1}$'. (This requires that the system be spatially confined.) In the experiments β_j had the value $0.702(m_1c^2)^{-1}$. Adopting $T = (k_b\beta_j)^{-1}$ as a reasonable *definition* of temperature, the question arises how the respective observers can *measure* it. The authors suggest that «a moving observer with rest frame $\sum'$ can *measure* T by exploiting a Lorentz invariant form of the equipartition theorem» (Cubero et al. 2007), in which the velocities of the particles are averages with respect to the $\sum'$ frame. On this basis the authors conclude that «a Lorentz-invariant gas thermometer on a purely microscopic basis» (Cubero et al. 2007) has been defined.

> Put differently, this intrinsic statistical thermometer determines the proper temperature of the gas by making use of simultaneously measured particle velocities only; thus, moving bodies appear neither hotter nor colder. (Cubero 2007, pp. 170601-4)

If these findings are correct what follows for the measurement of time from a Lorentz-invariant gas thermometer or gas clock? If the temperature of a body is not dependent on its state of motion – coffee on a fast-moving train has the same temperature as coffee on the platform – then it is imaginable that two observers moving inertially with respect to each other can employ the statistical thermometers to measure objectively the passage of time. Equally entropic clocks or pressure gas clocks are relativistically invariant. Philosophically, these findings have serious implications for the static view of time, associated with the block universe.

5. Conclusion

As mentioned above, in these considerations the passage of time is intimately related to physical, in particular thermodynamic processes. One conclusion to be drawn from these results is that both invariance and regularity are essential if relativistically moving observers are to agree on the passage of time, as measured by some clock. In mechanical clocks, in a relativistic context, the ticking is regular in each inertial system, but the rate of ticking is dependent on the velocity of the system. Hence the invariance criterion fails. But invariance does not fail in the gas clocks, considered above, which are based on the Lorentz-invariant parameters of pressure and entropy. Hence their ticking rates remain the same. In a Lorentz-invariant thermometer, based on velocity averages, the temperature rises in a regular fashion in the same way in both systems, hence temperature is Lorentz-invariant. In a similar way without knowledge of the regular motion of the sun, Archimedes and Eratosthenes could not compute the occurrence of midday at their respective locations. With respect to their different locations, the regular motion of the sun is invariant. According to the standard geometric interpretation of Minkowski space-time, there is no universal Now and both the simultaneity of relativity and the time dilation effect make clock time relative to the state of motion of the system. But if time is what the clock tells the observers according to their respective frames, the passage of time, so the argument runs, cannot be an objective feature of the physical world. Space-time is a four-dimensional manifold and the passage of time must be a human impression, due to the perspectival slicing of space-time, according to particular coordinates of the respective observers. As was pointed out above, it is hard to understand why this conclusion should follow, given the existence of Lorentz transformation rules, which allow the respective observers to compute their respective times. It is true that the mechanical clocks indicate the time relative to the velocity of the inertial system, but from this relativity it does not follow that time is merely a human illusion, only that the ticking rate is not invariant. The velocities of the respective systems must be known, if the observers want to compute the ticking of each other's clocks. If these quantities were not known, geometric time would be completely relative. But as opponents of the block universe point out, there are other Lorentz-invariant phenomena. The Lorentz-invariance of entropy, pressure and temperature allows us to envisage the construction of clocks, whose ticking rate remains the same, irrespective of the inertial motion of the system.

Such Lorentz-invariant clocks are not in contradiction to the well-known results of the Special theory of relativity,

> for there is nothing in the principle of relativity that specifies what particular physical variables, or functions of variables, shall be Lorentz-invariant. We *are* required to drop the prescription that *any* t variable, for no matter what process, is subject to a Lorentz transformation with change of relative state of motion. Time, instead of being a substratum entity which controls all physical phenomena, must now be regarded as a concomitant or measure of physical process [...]. (Schlegel 1977, p. 252; *italics in original*)

Traditionally, objections to the inference from the results of the Special theory of relativity to the human illusion of the passage of time have appealed to parameters like ds and c; however, these objections still remain within the standard geometric interpretation of Minkowski space-time. But the measurement of time must be based on physical phenomena, a conclusion, which – in the present context – is emphasized by the so-called axiomatic approaches. They are based on optical signals, which involve thermodynamic properties. Users of a Lorentz-invariant thermodynamic clock could infer that the passage of time is objective, since it is based on Lorentz-invariant parameters, like p, S and T. But it remains true – within the Special theory of relativity – that time is what the clock tells. They use thermal time. Whilst the standard inference to the unreality of time in Minkowski space-time relies on frame-dependent parameters, the inference to the reality of time in Minkowski space-time relies on frame-independent properties. But it seems to be no less legitimate than the first inference. This situation suggests that inferences as to reality or unreality of the passage of time in Minkowski space-time are conceptual in nature. Claims about a static block universe or a dynamic space-time do not follow deductively from the principles of the Special theory of relativity. The conclusions we draw seem to depend on the criteria we choose for drawing these inferences. As the inferences are conceptual in nature, the scientific theory, from which they are drawn, cannot conclusively falsify one inference at the cost of its rival. But the certainty, with which proponents of the block universe infer from the Special theory that time is a human illusion is thrown into doubt by the existence of invariant thermodynamic clocks in Minkowski space-time.

> What is at issue is not the validity of the Lorentz time transformation, which has been amply demonstrated, but whether its purview is an entire "meta"physical

> time, suffusing all of nature, or only an aspect, temporal in its properties, of physical interactions. (Schlegel 1977, p. 252)

The possibility of Lorentz-invariant clocks, within the Special theory, is incompatible with the inference to the block universe. Whilst a physical theory does not have the resources to prove or disprove conceptual inferences, which are drawn in its name, it remains entirely possible that one inference is more compatible with the underlying theory than its rival if all the facts are taken into account.

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