MARTINS, Roberto de Andrade. Use and violation of operationalism in relativity.
Manuscrito **5** (2): 103-15, 1981.

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USE AND VIOLATION OF OPERATIONALISM IN RELATIVITY

Separata de *Manuscrito*, vol. V, número 1

Campinas – São Paulo – Brasil
1981

USE AND VIOLATION OF OPERATIONALISM IN RELATIVITY *

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1 Introduction

The relation between philosophy or methodology of science and the actual practice of scientists has frequently been discussed. The older accounts supposed that scientists obeyed a set of methodological norms and followed an ordered sequence of activities in their research. Recent studies tend to emphasize the opposite, non-systematic and even a-rational aspects of scientific practice (Toulmin, 1977). As a contribution to the study of this theme, this paper presents a case-analysis of interactions between physics and epistemology: the interrelations between Einstein's theory of relativity and the so-called 'operational point of view' developed by Bridgman. This subject has already been specifically studied by Grünbaum (1954). He compared relativity to some special points of Bridgman's doctrines and concluded that Einstein's theory does not support them. I use a different approach, choosing to examine the broader aspects of operationalism common to several empiricist doctrines, instead of discussing details of one particular formulation. Other recent papers treat the related problem of Mach's influence on relativity (Zahar, 1973; Feyerabend, 1974; Schaffner, 1974; Zahar, 1977). However, the main point of this paper is not discussed there.

What is the central idea common to the recent forms of positivism and empiricism, and which became widely known among modern scientists through Bridgman's formulation?[1] I shall not try to describe it clearly, because its several forms are mutually incompatible. In a loose way, the word 'operationalism' will be used to denote the tendency which tries to rid science from undecidable questions, untestable propositions, and unobservable entities. In order to attain this goal, operationalism proposes the rejection of

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* This work has been supported by a research grant from the Brazilian National Council for Scientific and Technological Development (CNPq).

[1] Bridgman's basic books on operationalism are Bridgman (1927) and Bridgman (1936).

theoretical constructs which cannot be univocally linked to empirical descriptions.

Einstein admits that, in his youth, he acquired an epistemology related to operationalism, from his readings of Hume, Poincaré, and Mach (Einstein, 1949a, p. 53). The operational point of view is clearly present in Mach's works, where it is a consequence of his general conception of science. According to Mach, the aim of science is the economic description of experience, leaving aside causal explanations (Mach, 1904, p. 2, p. 457). Even fruitful models such as the wave picture for light or the atomic kinetic theory should therefore be rejected. It is well known that Mach refused the concepts of absolute time, absolute space, and absolute motion (Mach, 1904, pp. 217-234; pp. 482-492). This denial had a clear operational motivation.

Although Poincaré's ideas greatly differed from Mach's, it is possible to find among his writings many assertions of operational flavour (Poincaré, 1935, p. 113; Poincaré, 1897). But although Mach adheres coherently and radically to a program of elimination of undecidable questions, Poincaré allows a valid use for unobservables in physics: the explanation of phenomena (Poincaré, 1935, p. 143, p. 190, p. 200). It should be noted that Poincaré used the ether idea in all his scientific papers on electromagnetism (Poincaré, 1954), even after the rise of relativity.

2 Operational Aspects of Relativity

There are several known instances of operational statements and operational practices in Einstein's writings on relativity and epistemology. We may safely accept as true the following propositions:

a) Einstein consciously adhered to operationalism at the time of the building of special relativity (Bridgman 1949); he explicitly states operational principles in his early writings (Einstein, 1916a; Einstein, 1921, p. 26).

b) Positive practice of operational analysis: Einstein studied, in a way clearer than had been done before, the relations between space-time concepts and their measurement processes (Einstein, 1905); this clarification was a basic step for the creation of special relativity (Wertheimer, 1959; Gutting, 1972).

The significance of (a) and (b) is controverted. Some authors invoke one of Einstein's famous sentences [2] to suggest that he could have misunderstood his own method. Besides, as Bridgman himself pointed out (Bridgman, 1954), 'any person can make an operational analysis, whether or not he accepts what he supposes to be the thesis of "operationalism", and whether or not he thinks he is wasting time in so doing'. But a third important aspect must be remarked:

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[2] 'If yor wish to learn from the theoretical physicist anything about the methods which he uses, I would give you the following piece of advice: Don't listen to his words, examine his achievements' (Einstein, 1934).

(c) Negative (destructive) use of operationalism: Einstein refused the validity within physics of some theoretical ideas which could not be unambiguously linked to experience, such as absolute simultaneity, absolute space, ether, and absolute motion (Einstein, 1905).

These negative steps of special relativity (denial of 'unobservables') are usually described by Einstein and others as a kind of sound scientific procedure based on valid epistemological assumptions of old use (Einstein, 1967); d'Abro, 1950, pp. 430-431; Cassirer, 1953; p. 376; Reichenbach, 1949, p. 291). But we must remember that the ether dismissed by Einstein did have a scientific role in Lorentz's and Poincaré's theories: it provided an explanation of phenomena. In Lorentz's theory, the contraction of material bodies (which accounted for Michelson's results) was explained as a dynamic effect: the motion of the material body through the ether changed the forces between the electric charges which constitute matter, and in this way modified the dimensions of material bodies (Lorentz, 1895). Poincaré (1900) remarked that Newton's third law (principle of action and reaction) would not be valid in Lorentz's theory, if only material bodies were taken into account (the same result holds in special relativity). But the principle could be retained, and its global experimental validity explained, if the momentum of the ether was taken into account.

Unlike Lorentz, Einstein did not try to explain the relativistic phenomena – such as length contraction and time dilation. These results are deduced from the relativistic principles, but are not causally accounted for. According to an analysis by Grieder (1977), it was not by an historical chance that relativity did not develop these causal explanations: its structure prohibited it. Similarly, Einstein introduced the postulate of the constancy of light's speed *in vacuo* without trying to explain the reason of this paradoxical idea. We cannot say that it is explained by the law of addition of velocities, since this law is a theorem derived from that postulate.

These negative operational aspects of Einstein's work are not so easy to explain away as the former ones. Einstein could only support these negative steps (such as the dismissal of the ether as a superfluous concept) if he implicitly or explictly accepted the operational principle that anything (including causal explanations) which is not necessary to predict experimental facts is indeed superfluous to science. If he did not accept this general principle, his denial of the ether (and other negative steps) would be a gratuitous and incoherent procedure. Now, if these destructive aspects were not present, Einstein's relativity would not differ from Lorentz's and Poincaré's. So, the development of Einstein's special relativity was essentially based on some negative steps which can only be justified by an operational epistemology. I cannot see how could this attitude of Einstein's be distinguished from similar practices by Mach and other empiricists. Those who accepted and those who criticized relativity in its early development emphasized this epistemological basis. Sir Oliver Lodge accepted the main results of relativity, but could not accept its philosophical basis, because it accounted for the experimental facts without explaining them (Lodge, 1921a, 1921b).

In the historical development of general relativity, an operational concern may also be detected. One first instance: the old distinction between gravitational fields and 'absolutely accelerated or rotating' frames was denied any physical meaning by Einstein, because there was no empirical distinction between them (Einstein, 1916b, 1967). The introduction of this principle of equivalence, although justified by conformity to experience, was not explained by Einstein. Besides, Einstein tried to include in the general theory of relativity Mach's principle of relativity of inertia, which was supported on empiricism (Mach, 1904, pp. 220-234; Einstein, 1917). If absolute space were accepted as a valid physical concept, there would be no motivation for building general relativity. Even the formalism of this theory (tensor calculus) was chosen in order to allow a formulation of physical laws that showed no preferred reference frame. So, the basic motivation was to eliminate unobservables from physics.

At the time of the birth of the general theory of relativity, it was regarded as a natural extension of the special theory of relativity, and was thought to be based on the same epistemological ideas. Today, while the special theory is usually described as a successful application of operationalistic ideas, the general theory is seen as based on a different philosophical view. It is indeed very easy to show some aspects of the general theory of relativity which violate operationalism. Although space-time coordinates are basic concepts in general relativity, Einstein did not describe any procedure for their measurement. He could not implicitly assume the old empirical coordinations developed in special relativity, because the measurement process must be different. General relativity, therefore, was built upon unmeasurable magnitudes. The first valid construction by which it is possible to determine experimentally space-time intervals within the framework of general relativity is claimed to be the one developed by Marzke in 1959 (Marzke and Wheeler, 1964). If this claim is valid, it shows that no operational elucidation was provided for one of the basic concepts of general relativity for more than 40 years. Even Bridgman, who described operationalism as the outcome of Einstein's relativity, complains that the general theory was not built according to the operational point of view (Bridgman, 1949).

The advent of general relativity is generally described as the turning point of Einstein's epistemology (Frank, 1949a, Einstein, 1934). In his latter writings, he directly denies operationalism (Einstein, 1944, Einstein, 1949b). However, it does not seem that Einstein and other relativists were aware of this breakdown before 1920. It has been suggested that Einsteins's conscious denial of operationalism was a psychological reaction to the postumous publication of Mach's criticism of relativity[3] (see Holton, 1965).

Even those who notice the non-operational aspects of general relativity seldom remark that even the formulation of special relativity showed

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[3] In the preface of his *Principles of Physical Optics* (written in 1913), Mach criticizes Einstein's relativity. This book was published only in 1921, and shortly after reading it, Einstein produced his first recorded denial of Mach's phiolsophy.

strong violations of operationalism. Most authors seem to believe that Einstein produced an operational elucidation of all the physical magnitudes introduced in special relativity, in a way similar to his analysis of spatio-temporal measurements. This is possibly due to the usual limitation of philosophical analysis to the postulates and kinematical part of special relativity. However, even in his first paper, Einstein developed a relativistic *dynamics* where the empirical elucidation is not carried to concepts such as force, energy, and mass. These variables are introduced and retained in special relativity by formal analogy to classical mechanics. In the early development of the theory, nobody cared about their measurement.

3 Non-Operational Concepts in Special Relativity

Einstein's (1905) *Zur Elektrodynamik bewegter Korper* was composed in three parts: introduction, kinematics, and electrodynamics. In the last section Einstein enumerates 'the properties of the motion of the electron which result from the system of equations . . . and are accessible to experiment':

1) The ratio between electric and magnetic powers of deflection of an electron:

$$A_m/A_e = v/c$$

2) The relation between the kinetic energy of an electron and the accelerating potential:

$$P = \int \vec{X}/\vec{x} = mc^2 \left[(1-v^2/c^2)^{-1} - 1 \right]/e$$

3) The radius of curvature of an electron moving in a normal magnetic field:

$$R = (mc^2/e).(1-v^2/c^2)^{-1/2}.v/cN$$

The first prediction does not differ from the classical one. The second is verbally described as a relation between *kinetic energy* and accelerating potential, but Einstein did not imply that this kinetic energy should be measured by stopping the electrons and transforming their motion energy in any other measurable form (e.g., in thermal energy, as was done by Bertozzi (1964) in his experiments on relativistic dynamics). Einstein's paper shows that he supposed that the three tests should be proved by measuring: the speed v of the electrons, their *rest* mass m, their (rest) charge e, the (rest) values of the electric and magnetic fields X and N. All of these magnitudes could be measured by classical procedures.

Among his predictions, Einstein does not include any possible test of mass variation of the accelerated electrons. It has been suggested (Miller, 1977) that he omited it because he knew that his prediction

$$\text{transverse mass} = m/(1-v^2/c^2)$$

was different from Lorentz's

$$\text{transverse mass} = m/(1-v^2/c^2)^{1/2}$$

and would not agree with Kaufmann's experimental results. But it seems that Einstein's reasons were different. At §10 of his paper, he assumes that

$$\vec{F} = m.d^2\vec{r}/dt^2 = e.\vec{E}$$

and derives from this relation (and the transformation formulas for the electromagnetic field) the values for transverse and longitudinal masses of the electron. He then remarks that 'with a different definition of force and acceleration, we should naturally obtain other values for the masses. This shows us that in comparing different theories of motion of the electron we must proceed very cautiously'. (Einstein, 1905). So, it seems that he did not consider the mass of a moving electron as directly measurable and therefore any assertion about this magnitude could not be definitely tested.

So, the mass of a moving electron was not a measurable magnitude, in Einstein's theory. Was there any other dynamical magnitude which could be measured in different referential systems?

In classical dynamics, some dynamical vector magnitudes (force, linear momentum) and some scalars (mass, work, energy) were used. They obeyed classical transformation laws; they had some (vector or scalar) additivity properties; they were supposed to obey some conservation laws (mass, momentum, energy); and had also some mutual relations. This whole set of properties was testable, because some of the magnitudes could be measured independently: mass, force, energy changes. Now, this set of properties could not be mantained in special relativity, because it is incompatible with relativistic kinematics (Martins, 1979). Particularly, the basic newtonian concepts of mass and force loose their univocity, and do not have any more an operational meaning in relativistic mechanics, unless a new empirical elucidation of these magnitudes is provided (Ciedymin, 1973; Frank, 1946, pp. 455-456). But, in order to build a relativistic dynamics, kinematical concepts (space, time, velocity, etc.) are not enough; at least one dynamical magnitude must be introduced. And in order to characterize this magnitude, some of its classical properties could be retained, but not the whole set. Which should be chosen?

The choice of the properties of relativistic dynamical variables was not an easy one. Einstein first tried to retain the second law of Newton in its 'acceleration form' ($\vec{F} = m\vec{a}$). He uses forces as the basic dynamical magnitude, measurable by a spring balance (dynamometer). But Planck convinced him that it was more interesting to drop this form in order to retain the simplest formulation of the laws of conservation of energy and momentum (Planck, 1906).

The choice of the new concept of force led to some unexpected difficulties. Assuming the classical definition of torque and the old laws of statics, Lewis and Tolman (1909) obtained a law of force transformation which was not the same as that obtained by electrodynamical considerations. Therefore, some theorems of classical mechanics needed a reformulation. There was a delicate choice among many alternatives.

Perhaps relativistic dynamics could be introduced by means of electrodynamics. But a circularity arises, because the measurement of electric charge and of the electromagnetic vectors depend on the measurement of force or some other dynamical magnitude. As was remarked above, Einstein took *force* as the basic measurable magnitude, in his 1905' paper. There, he explicitly says that electromagnetic magnitudes should be related to force measurements. Nevertheless, the behaviour of a dynamometer *in motion* is not analysed, and although it may be supposed that, at low speed, it retains its classical properties, this is not possible in the general case. So, the empirical meaning of the electromagnetic vectors and of a charge *in motion* is not elucidated, and they cannot be used to elucidate other concepts.

What most interests us is this question: if the transformation laws of relativistic dynamics are to be testable, we must suppose that some dynamic measurement can be done over a moving body. Which dynamical measurement is possible in these conditions? Mass has already been excluded. If kinetic energy, forces or linear momenta could be measured, the other dynamical variables could be calculated, and relativistic dynamic transformations could be tested. None of these alternatives was followed by Einstein. He did not really consider the problem of testability of relativistic transformations of dynamical magnitudes. This may also be inferred from latter papers. In his 1907 essay (Einstein, 1907), he defines the vector magnitude $\vec{K}$:

$$K = d/dt\, [m\dot{\vec{x}}/(1-v^2/c^2)^{1/2}]$$

He proves that this magnitude performs, in electrodynamics, a (formal) role similar to the classical force concept, and states that, in the general case, this equation 'does not have any physical content, but have to be considered as equation of definition of force' (Schwartz, 1977). From several instances of Einstein's use of the expression 'physical content', we may infer that he means that this new force concept is not univocally related to any empirical measurement procedure.

In 1935, Einstein tried to formulate relativistic dynamics independently of electromagnetism. In so doing, he avoided completely the concept of force (Einstein, 1935) while retaining those of energy and momentum. But he does not discuss the measurement process of these magnitudes. We may safely conclude that in the building of Einstein's special relativity the mass of a moving body, its momentum, its energy, and the forces which acted upon it, were not measurable magnitudes, and therefore any statement such as the transformation laws of relativistic dynamics had no testable meaning.

It might seem that, even if this really was the case in its historical development, it does not happen in our contemporaneous relativity. But this is not true. The evidence may be taken from Arzeliès' treatise on relativity. This is possibly the most complete presentation of relativity in recent times, as it embodies an historical view of all important (including confliting and unortodox) formulations of relativity. Now, although Arzeliès dedicates several chapters to the study of the measurement of kinematical magnitudes, emphasizing the importance of this operational analysis (Arzeliès, 1955, p. 2, p. 96), he barely studies the measurement of dynamical ones. In the first volume of the dynamical part of his work, he supposes that forces are the basic dynamical magnitudes, and that they are to be measured by means of elastic deformations, that is, by dynamometers (Arzeliès, 1957, p. 143). But while discussing the force which acts upon a moving body, he shows that this concept leads to great difficulties. In fact, if forces are to be measured by dynamometers, no change of the value of a force could arise when they are observed from different referential systems, that is, forces should be invariants, and this is not what is supposed in special relativity. Palacios' criticism is certainly just in this point: 'I fail to see how a given force can be altered by the motion of the observer. Consider a dynamometer which reads *F* newtons when the particle is attached to it. How can the reading become *F' newtons* when looked at by a moving observer?' (Palacios, 1965).

One possible conclusion is the view that the dynamical transformations of special relativity are not physical laws, because they cannot be tested by experiment: 'Only statements which contain just lengths and time durations remain unchanged and deserve the name of physical laws' (Arzeliès, 1957, p. 154). We may certainly conclude that the experimental status of dynamical transformations is different from that of kinematical transformations. 'With the given physical interpretation of coordinates and time, this (the use of Lorentz-transformations) is by no means merely a conventional step, but implies certain hypotheses concerning the actual behaviour of moving measuring-rods and clocks, which can be experimentally validated or disproved' (Einstein, 1949a, p. 57). In this context, it may be said that the relativistic dynamical transformations *are conventional.*

There are several modern attempts at closed axiomatic formulation of relativistic dynamics, such as one by Stiegler (1959). In all these, there is no reference to the problem of measurement of dynamical variables in moving systems.

Did the absence of operational analysis of some magnitudes give rise to any problems in special relativity? Yes, it did. The lack of empirical elucidation of concepts usually gives rise to controversies (empiricism was created exactly to eliminate undecidable disputes). The problem of a relativistic statics has not yet been answered (O.Gron, 1978), and even simple problems such as the right-angle lever paradox still produce controversies (Nickerson and McAdory, 1975). Two other important cases are seen in special relativity: the almost century-old problems of (a) relativistic thermodynamics, and (b) momentum of light in dielectrics. These problems may be shortly described as follows: there are two principal conflicting formulations both of relativistic thermodynamics and of the mechanical properties of electromagnetic radiation in refractive media. According to Einstein and others, temperature and heat transform as:

$$\begin{aligned} \delta Q &= \delta Q_0 (1-v^2/c^2)^{1/2} \\ T &= T_0 (1-v^2/c^2)^{1/2} \end{aligned}$$

According to Ott and others, they have the opposite transformations:

$$\begin{aligned} \delta Q &= \delta Q_0 (1-v^2/c^2)^{1/2} \\ T &= T_0 (1-v^2/c^2)^{1/2} \end{aligned}$$

(for references, see Arzeliès, 1971, and Guessous, 1970).

As to the momentum of light inside dielectrics, it was derived by Ninkowski and von Laue that it increases inside dielectrics, proportionaly to the refractive index n of the medium: $p = p_0.n = n.U/c$. Abraham and others deduced that it should instead *decrease* in dielectrics, inversely proportional to the refractive index: $p = p_0/n = U/nc$ (see Burt and Peierls, 1973, Skobel'tsyn, 1973, and references therein).

In both these controversies, appeal to experiment for deciding the question is not possible, because there are no accepted relations between theoretical magnitudes and measurement processes. According to Landsberg and collaborators, 'only the rest values of temperature, etc. have a physical meaning'. It is generally agreed that 'the relative merits of the various formulations must in the last reckoning be tested by application to experiments, although it is very difficult to envisage any experiments suitable for such a comparison' (Ter Haar and Wergeland, 1971).

An operational formulation of these fields os special relativity – such as Giles' (1964) proposal of an operational relativistic thermodynamics – could eliminate these controversies. Should this be done? Or should we perhaps formulate the whole of relativity in a way completely free of operational ideas, as some modern axiomatizations do? From the philosophical point of view, 'we cannot urge the necessity of building only on experience in one part of physics and evade that necessity in another', as Dingle put it (1949). It is also possible to formulate a theory which has the same empirical content as Einstein's relativity, but does not use Einstein's postulates of his elucidation of simultaneity. But in spite of their possible formal beauty, any formulation which does not include reference to empirical relata is scientifically sterile and is not equivalent to Einstein's theory in its philosophical basis. It cannot be taken as its substitute in a study of the relations between epistemology and scientific practice, such as the present one. The confusion between historical evolution and rational, didactic, or axiomatic reconstructions has sometimes given rise to controversies like that between Holton and Grünbaum about the relevance of Michelson's experiment in special relativity (see Gutting, 1972, and references therein). We hope that similar confusions will not develop from this paper.

4 Conclusions

We have shown that special relativity presents some instances of operational practice, both positive (empirical elucidation of some concepts) and negative (dismissal of non-empirical concepts such as absolute time and space, ether, absolute motion). But neither of these attitudes has been coherently carried through all the theory of special relativity. This is a clear instance of epistemological oportunism in a physical theory: Einstein invoked operationalistic principles in order to deny some ideas which could disturb the development of relativity; but at other points he used some other ideas which could be equally refused on the same epistemological ground. It cannot be claimed that this occurred because the empirical elucidation of other concepts (such as the force acting on a moving body, its mass, its temperature) was useless. Actually, if any author succeeded in establishing methods for measuring thermodynamical and dynamical variables of moving systems, this would be acknowledged as a valuable contribution to this physical theory. It would probably eliminate some old controversies, enhance the testability of relativity, and suggest some new applications of the theory. Besides, it cannot be denied that this elucidation was possible even in 1905. The operational elucidation of dynamical magnitudes needed no new experimental facts, and therefore it could have occurred in the early stage of special relativity.

It is also important to notice that the empiricism of relativity was not a mere appendix to the physical theory. The negative steps of relativity could not be undertaken except on the basis of an operational-like epistemology. So, these ideas were really essential for the development of Einstein's theory.

In recent times several claims have been produced which deny any logical connection between operational ideas and the theory of relativity. I think that these opinions have only arisen after the discovery of the philosophical failure of the operational point of view, and not before. The attitude of these new philosophers who deny the relation between operationalism and relativity is understandable: they accept and praise relativity, and do not want to see it linked to an invalid philosophy. But Bridgman and other philosophers who vindicate the strong relation between operationalism and Einstein's theory are not wrong. What cannot be claimed is that operationalism and relativity should both be accepted or refused together. The success of an application of an idea is not a guaranty of that idea. If it is accepted that relativity is a useful theory and that operationalism was basic to its development, it may be concluded that operationalism may generate useful theories, but not that operationalism is valid. And if operationalism is proved to be an untanable epistemology (as seems the case) and it is accepted that relativity developed as an application of operationalism, we may conclude that Einstein's work could validly be criticized, and that he had no right to dismiss the ideas of absolute motion, ether, etc. But we cannot conclude that relativity theory should be dismissed altogether.

It is also important to conclude that, even when a scientist is as deeply commited to an epistemological principle, as Einstein seemed to be, it happens that he can overlook its application in many important parts of his scientific work. This does not prove that epistemology is irrelevant to scientific practice. If any epistemological principle is accepted, it entails consequences in the scientific practice. If instead of operationalism scientists accepted that the aim of science is to provide a causal explanation of phenomena, they should refuse the early theory of relativity. The violations of operationalism in Einstein's work are not just a proof that Einstein's method was not operational. Together with the evidence of the importance of the uses of operationalism by Einstein, it proves that Einstein's work cannot be described by any coherent set of methodological rules. I think that the development of relativity is an instance of the easy acceptance of philosophical inconsistency within science, by physicists.

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RESUMO

Einstein conhecia e aceitava idéias filosóficas aparentadas ao operacionalismo de Bridgman na época em que desenvolvia a teoria da relativaidade. Pode-se detetar essas influência nas teorias especial e geral da relatividade. Alguns dos passos básicos de Einstein foram essencialmente operacionalistas. Assim, é comum a opinião que supõe ser completamente efetuada, na teoria especial. de modo coerente, a elucidação operacional das grandezas físicas. Neste artigo, porém, apresentam-se exemplos de grandezas físicas utilizadas na relatividade especial – como a força que age sobre um corpo em movimento, sua massa e sua temperatura – que não eram mensuráveis. Isso revela uma inconsistência epistemológica no trabalho inicial de Einstein.

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