Chapter 9
The Adolescence of Relativity: Einstein, Minkowski, and the Philosophy of Space and Time

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Abstract An often repeated account of the genesis of special relativity tells us that relativity theory was to a considerable extent the fruit of an operationalist philosophy of science. Indeed, Einstein's 1905 paper stresses the importance of rods and clocks for giving concrete physical content to spatial and temporal notions. I argue, however, that it would be a mistake to read too much into this. Einstein's operationalist remarks should be seen as serving rhetoric purposes rather than as attempts to promulgate a particular philosophical position – in fact, Einstein never came close to operationalism in any of his philosophical writings. By focussing on what could actually be measured with rods and clocks Einstein shed doubt on the empirical status of a number of pre-relativistic concepts, with the intention to persuade his readers that the applicability of these concepts was not obvious. This rhetoric manoeuvre has not always been rightly appreciated in the philosophy of physics. Thus, the influence of operationalist misinterpretations, according to which associated operations strictly *define* what a concept means, can still be felt in present-day discussions about the conventionality of simultaneity.

The standard story continues by pointing out that Minkowski in 1908 supplanted Einstein's approach with a realist spacetime account that has no room for a foundational role of rods and clocks: relativity theory became a description of a four-dimensional "absolute world." As it turns out, however, it is not at all clear that Minkowski was proposing a substantivalist position with respect to spacetime. On the contrary, it seems that from a philosophical point of view Minkowski's general position was not very unlike the one in the back of Einstein's mind. However, in Minkowski's formulation of special relativity it becomes more explicit that the content of spatiotemporal concepts relates to considerations about the form of physical laws. If accepted, this position has important consequences for the discussion about the conventionality of simultaneity.

Keywords Special relativity · Conventionalism · Operationalism · Simultaneity · Einstein · Minkowski

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9.1 Introduction

At the end of the introductory section of his “On the electrodynamics of moving bodies” Einstein [8, p. 892; 24, p. 277] famously declares: “The theory to be developed is based – like all electrodynamics – on the kinematics of the rigid body, since the assertions of any such theory have to do with the relationships between rigid bodies (systems of co-ordinates), clocks, and electromagnetic processes. Insufficient consideration of this circumstance lies at the root of the difficulties which the electrodynamics of moving bodies at present encounters” (English translation from [17, p. 38]). When Einstein subsequently starts discussing the notion of time he elaborates on the same point and warns us that a purely theoretical, mathematical, description “has no physical meaning unless we are quite clear as to what we understand by ‘time’.” He goes on by explaining that we need to provide our concepts with concrete physical content and that for the case of time at one spatial position the sought *definition* (Einstein’s term) can simply be given as “the position of the hands of my watch” (situated at the position in question). Time thus defined is a purely local concept, however, so that we need a further definition in order to compare times at different positions. For this reason Einstein famously engages in a discussion of simultaneity. He briefly considers the possibility of assigning to distant events the time indicated by one fixed clock at the moment a light signal from the events reaches this clock, but rejects this possibility because the time thus assigned would depend on the location of the standard clock (which would have as a consequence that physical laws would become position-dependent too). A much better idea is to work with synchronized clocks without any hierarchical ordering between them. This then finally leads to the introduction of Einstein’s famous procedure for synchronizing clocks: synchronicity is *by definition* achieved when all clocks are set such that the velocity of light, measured with their help, becomes the same in all directions. Now the characterization of time in a frame of reference has become complete: “the ‘time’ of an event is the indication which is given simultaneously with the event by a stationary clock located at the place of the event, where this clock should be synchronous for all time determinations with a specified stationary clock” [24, p. 279; 17, p. 40].

These passages, and others in the 1905 paper, appear to put forward an undeniably operationalist conception of spatial and temporal notions. Coordinates are identified with notches in rigid material axes, distances *are* what is measured by rigid measuring rods, and time *is* what is indicated by the hands of synchronized clocks. This operationalist flavour becomes even stronger because Einstein repeatedly uses the term “definition” in his analysis: time is *defined* via operations with clocks, and thus apparently has no other meaning than what results from these operations. Because definitions, as the term is used in its natural scientific habitat – logic and mathematics – are the results of our free decisions and cannot be true or false, this suggests that Einstein is telling us here that spatial and temporal notions, among them “simultaneity”, are purely conventional in character. So a twofold philosophical message seems to be implied: first, fundamental physical concepts must be defined via concrete physical operations in order to be meaningful at all and second, these definitions have the status of conventions.

Einstein's statements in these pages have had an enormous influence in twentieth century philosophy of science. Among logical positivists it was one of the motivations for developing the doctrine of "coordinative definitions," according to which physical concepts (like "time") should be coordinated to concrete physical things and procedures. Schlick [22], and in his footsteps [21], emphasized that this coordinatization is fundamentally conventional in character; Reichenbach elaborated this idea in famous detail in his analysis of simultaneity. Percy Bridgman, the founder of operationalism, took his inspiration from Einstein's analysis as well. In his contribution to *Albert Einstein: Philosopher-Scientist* [23], Bridgman [1] wrote: "Let us examine what Einstein did in his special theory. In the first place, he recognized that the meaning of a term is to be sought in the operations employed in making application of the term. If the term is one which is applicable to concrete physical situations, as "length" or "simultaneity", then the meaning is to be sought in the operations by which the length of concrete physical objects is determined, or in the operations by which one determines whether two concrete physical events are simultaneous or not." Bridgman went on to complain that in his General Theory of Relativity Einstein seemed to have forgotten some of his own methodological lessons.

Bridgman must have been disillusioned by the reply Einstein gave to his admonitions. In his "Remarks to the Essays Appearing in this Collective Volume" [23], Einstein squarely rejected operationalism, both in the context of special and general relativity. That Einstein here opposed operationalism in such strong terms is remarkable: did Einstein change his beliefs, or remained his convictions more or less the same and are there ways of reading his 1905 statements other than those proposed by the logical positivists and operationalists? Of course, one must be careful in interpreting the documentary material here: what Einstein wrote later in his career need not at all faithfully reflect his attitudes as a young scientist. However, after reviewing the evidence, we shall indeed conclude in this paper that another, non-operationalist, reading of Einstein's early work is appropriate. But let us first return to what perhaps may be called "the standard account".

The usual story about the genesis of special relativity theory says that after Einstein's operationalist introduction of the theory, Minkowski in 1908 proposed a very different view. Minkowski interpreted special relativity as a geometrical description of a four-dimensional spacetime manifold, which he called "the Absolute World". According to this new point of view relativity theory does not depend on the coordinatization of events with the help of rods and clocks: it is a theory about an independent spacetime manifold that possesses an inbuilt geometrical structure and subsists even if there are no rods and clocks at all.

Although it would be an exaggeration to say that this characterization of Minkowski's work misses the mark altogether, I believe that both the emphasis on the difference between Minkowski and Einstein *qua* philosophical outlook, and the insistence that Minkowski posited the independent reality of a four-dimensional spacetime manifold, are misplaced. As I shall argue, Einstein no less than Minkowski thought of relativity as a theory about the general form of physical laws, without any special status for rods and clocks. Further, Einstein had misgivings about space and time as entities existing by themselves; but likewise Minkowski expressed doubts about empty spacetime and stated as his belief that special relativity is best seen as a theory about the relations between material systems. Although it is true that Einstein's presentation in which rods and clocks figure prominently is replaced by Minkowski with one in which fundamental particles and fields are basic, I believe that this does not signify a fundamental philosophical difference between Einstein and Minkowski.

Indeed, the picture that will emerge from the analysis given in this paper is that Minkowski did not give a completely new philosophical turn to relativity theory but rather completed, in a mathematically sophisticated and elegant way, the programme that Einstein had in mind. This conclusion has consequences for the status of the spacetime concepts that occur in the Einstein-Minkowski theory. In particular, new light is shed on the status of relativistic simultaneity. This is the final issue that we shall address. We shall argue that from a correctly understood Einsteinian–Minkowskian viewpoint simultaneity in special relativity is not more conventional than other fundamental physical concepts.

9.2 Einstein and the Definition of Space and Time

The 1905 paper is not the only place where Einstein expresses himself in a way that suggests operationalist sympathies. It is striking that even much later, in the Autobiographical Notes – the very same volume we referred to above [23] – we find Einstein reminiscing about his discovery of special relativity with the following words: "One had to understand clearly what the spatial co-ordinates and the temporal duration of events meant in physics. The physical interpretation of the spatial co-ordinates presupposed a fixed body of reference, which, moreover, had to be in a more or less definite state of motion (inertial system). In a given inertial system the co-ordinates meant the results of certain measurements with rigid (stationary) rods. If, then, one tries to interpret the time of an event analogously, one needs a means for the measurement of the difference in time. A clock at rest relative to the system of inertia defines a local time. The local times of all space points taken together are the 'time' which belongs to the selected system of inertia, if a means is given to 'set' these clocks relative to each other" [23, p. 55]. Historians of science often warn us not to rely too much on (much) later accounts scientists give of the way in which they made their discoveries: later experiences may very well have coloured and distorted their memories. But here we find an almost verbatim repetition of the relevant passages from the 1905 paper itself, including the use of the term *define*, and with the explanation that space and time coordinates *mean* what is indicated by rods and clocks; and all this without any accompanying comment that might indicate that Einstein in the nineteen-forties deemed some kind of qualification of his 1905 statements necessary. So we may safely assume that Einstein is here expressing the same view as the one he put forward in his original relativity paper. This is striking, most of all because elsewhere in these same autobiographical notes, and also in Einstein's "Replies" in the same volume [23] we find an explicit and strong rejection of operationalism as a viable philosophy of science.

As we already mentioned, Einstein's resented Bridgman's characterization of special relativity as a fountainhead of operationalism. The essential part of his Reply reads: "In order to be able to consider a logical system as physical theory it is not necessary to demand that all of its assertions can be independently interpreted and 'tested' 'operationally'; *de facto* this has never been achieved by any theory and can not at all be achieved. In order to be able to consider a theory as a *physical* theory it is only necessary that it implies empirically testable assertions in general" [23, p. 679]. Einstein made the same point in greater detail in his Reply to Reichenbach. In his contribution to the Einstein Volume, Reichenbach had contended that the philosophical lesson to be drawn from relativity theory was that basic physical concepts must be given meaning by means of "co-ordinative definitions": it is only the "co-ordination" of a concrete physical object or process to the concepts in question that bestows physical significance on them. "For instance," Reichenbach wrote [23, p. 295], "the concept "equal length" is defined by reference to a physical object, a solid rod, whose transport lays down equal distances. The concept "simultaneous" is defined by the use of light-rays which move over equal distances. The definitions of the theory of relativity are all of this type; they are co-ordinative definitions." Reichenbach continued by explaining that this definitional character of basic physical concepts implies that they are *arbitrary*. "Definitions are arbitrary; and it is a consequence of the definitional character of fundamental concepts that with the change of the definitions various descriptional systems arise. Thus the definitional character of the fundamental concepts leads to a plurality of equivalent descriptions. All these descriptions represent different languages saying the same thing; equivalent descriptions, therefore, express the same physical content." In his response Einstein famously staged a dialogue between Reichenbach and Poincaré, later in the dialogue replaced by a "non-positivist"; Einstein himself clearly being on the side of the non-positivist camp. Against the idea of coordinative definitions Einstein levelled the objection that any concrete physical object is subject to deforming forces, and can therefore not be used to *define* concepts. We need a *theory* of these deforming influences in order to be able to correct for them, and such a theory already uses a notion of length. Therefore, we must know what "length" is prior to the determination of the undisturbed length of any measuring rod. From this Einstein concludes that a concept like "equality of length" cannot be defined by reference to concrete objects at all; such concepts "are only indispensable within the framework of the logical structure of the theory, and the theory validates itself only in its entirety [23, p. 678]."

These remarks are in accordance with Einstein's often-expressed conviction that scientific theories and laws cannot be *derived* from experience but must prove their value when, once formulated as "free creations of the human mind", they are confronted as a whole with experience. With respect to space and time, we find this attitude clearly present in the lecture *Geometry and Experience* ([14, pp. 232–246];

German original *Geometrie und Erfahrung* [12]). In *Geometry and Experience* Einstein writes: “The idea of the measuring rod and the idea of the clock in the theory of relativity do not find their exact correspondence in the real world. It is also clear that the solid body and the clock do not in the conceptual edifice of physics play the part of irreducible elements, but that of composite structures, which must not play any independent part in theoretical physics.” One might wonder how this statement, made relatively soon after the discovery of relativity theory, can be squared with the role assigned to rods and clocks in the 1905 paper. Einstein is quick to answer this question. In the same 1921 lecture he continues: “It is my conviction that in the present stage of development of theoretical physics these concepts (i.e., rods and clocks) must still be employed as independent concepts; for we are still far from possessing such certain knowledge of the theoretical principles of atomic structure as to be able to construct solid bodies and clocks theoretically from elementary concepts.” Einstein goes on by explaining that the problem of deforming forces need not be prohibitive in practice: by comparing different solid bodies, of different constitution, we may obtain information about the order of magnitude of the deformations and we can then make appropriate corrections that suffice for practical purposes.

In a short, and not very well known, contribution to the German literary journal *die neue Rundschau*, Einstein [13] attempted to explain the situation to a general audience. To answer the question whether Euclidean geometry or some other geometry applies to the physical world, Einstein tells us, we have to choose between two possible points of view. Either we assume that geometrical concepts correspond, in an approximate fashion, to concrete physical objects — this is the attitude of the working physicist, and without it the creation of relativity theory would have been impossible. Or one assumes from the beginning that geometry by itself is not about real objects, but that only the *combination* of geometry and physics makes contact with physical reality. The latter point of view is probably, Einstein says, the one that is best for a systematic presentation of an already fully elaborated physics, of which we know the laws. In this case, the answer to the question of which geometry pertains to the physical world depends on how ‘simple’ the associated physics becomes when we choose the geometry in question.

The first point that consistently emerges from these statements is that the unit of length may only be supposed to be realized by a “theoretical” object, an *ideal* rod, which can merely be approximated by concrete objects. Although there is no reference to deforming forces and theoretical approximations in the 1905 paper, we may safely assume that even at this early stage Einstein, having received part of his physics training in the laboratory, saw the situation in this light – however, there was evidently little motivation for him to dwell on these distracting epistemological issues in the context of the introduction of his radically new physical ideas. That actual concrete objects do not fully represent theoretical space-time standards is an almost obvious thing, from a physical point of view. Indeed, in his early review article on special relativity, *Über das Relativitätsprinzip und die aus demselben gezogen Folgerungen*, written very soon after the 1905 paper, Einstein [9] repeated that for the assignment of spatial coordinates rigid rods are needed; but he added a footnote

[24, p. 437] saying that instead of referring to “rigid” rods we could as well speak of solid bodies “not subject to deforming forces”, clearly indicating that he was aware of the complications.

A second point that stands out is that Einstein did not think that rods and clocks have a truly foundational role to play. It is only because in everyday situations we are accustomed to thinking of rods and clocks for determining space and time coordinates, and are not able to directly describe these devices in terms of fundamental physical theory, that it is expedient to introduce them to fix what we are talking about. This is a practical decision, made for the time being; “with the obligation, however, of eliminating it at a later stage of the theory” (Einstein in [23, p. 59]). Thus, Einstein says that as soon as a direct characterisation via fundamental physical theory becomes available, this treatment will have to replace the rods-and-clocks account on the level of foundational considerations. This pragmatic attitude with respect to rods and clocks is a far cry from the idea that these devices *define* length and time!

There are two documents from the first few years after 1905 in which Einstein makes more than casual remarks on the status of simultaneity. In a 1910 paper published in French ([10]; [16], pp. 131–174) Einstein gives a general overview of special relativity, with particular attention to its epistemological foundations. As he wrote in a letter to Laub ([16], p. 175) this paper “comprises a rather general discussion of the epistemological foundations of the theory of relativity, no new views whatsoever” (“eine ziemlich breite Ausführung der erkenntnistheoretischen Grundlagen der Relativitätstheorie, gar keine neue Überlegungen”). In this article we find an extensive and interesting discussion of the relativistic conception of time. The discussion ([16], pp. 146–147) starts with the observation that we can *measure* time with the help of clocks (“Pour mesurer le temps nous nous servirons d’horloges”), continues with the assertion that we are obliged, by the principle of sufficient ground, to admit that subsequent periods of a clock take equally long periods of time (“... que nous soyons obligés d’admettre – en vertu du principe de raison suffisante – que...”), but then suddenly shifts to definition-terminology: the number of periods indicated by a clock *defines* the lapse of time, Einstein concludes. He goes on by stating that this definition of “local time” is not enough; we need to say something additional about simultaneity (“La définition est alors insuffisante: il faut la compléter.”) He explains this with an extensive exposition about the importance of setting clocks with respect to each other for the description of processes that are not restricted to one spatial position, and ends with a remarkable explanation of the synchronisation procedure.

“Let us first make available a means for sending signals from A to B and vice versa. This means must be such that we have no reason whatsoever to believe that the transmission phenomena in the direction AB differ in any respect from those in the direction BA. In this case, it is evident that there is only one way to set the clocks in B and A so that the signal from A to B takes the same time – measured with the mentioned clocks – as the one going from B to A.” (“Donnons-nous d’abord un moyen pour envoyer des signaux soit de A en B, soit de B en A. Ce moyen doit être tel que nous n’ayons aucune raison pour croire que les phénomènes de transmission des signaux dans le sens AB diffèrent en quelque chose des phénomènes de transmission des signaux dans le sens BA. Dans ce cas, il est manifeste qu'il n'y a qu'une seule manière de régler l'horloge de B sur celle de A de façon que le signal allant de A en B prenne autant de temps – mesuré à l'aide des dites horloges – que celui allant de B en A" ([16], p. 149)). After this justification, the standard ("$\varepsilon = {}^1\!/_2$") formula appears. But Einstein is not ready yet: he continues by pointing out that in principle we could use *any* signal for this procedure as long as we can be sure about the equal signal speeds in the two directions. "But we will give preference to light signals in vacuum, because as the synchronization requires the equivalence of the to and fro ways, we shall have this equivalence by definition since by virtue of the principle of the constancy of the speed of light, light in vacuum always propagates with the speed c. We therefore shall have to set our clocks such that the time for a light signal to go from A to B will equal that needed by a similar signal to go from B to A." ("Cependant, … nous donnerons notre préférence à ceux où l'on fait usage de rayons lumineux se propageant dans le vide, car, le réglage exigeant l'équivalence du chemin d'aller avec celui du retour, nous aurons alors cette équivalence par définition, puisque, en vertu du principe de la constance de la vitesse de la lumière, la lumière dans le vide se propage toujours avec la vitesse c. Nous devrons donc régler nos horloges de façon que le temps employé par un signal lumineux pour aller de A en B soit égal à celui employé par un même signal allant de B en A" ([16], p. 150)).

It is true that the word "definition" occurs in this exposition, but the text makes it clear that no arbitrary stipulation is meant. Rather, the idea expressed by "defining" simultaneity via sending light signals to and fro is that we can be sure about the validity of this synchronization procedure, given the light principle. Similarly, in the case of the comparison of successive periods of a periodic process (a clock) we saw Einstein invoking the principle of sufficient reason to justify the "definition" of the equality of these intervals. Evidently, Einstein had no qualms in letting the justification of such "definitions" depend on prior theoretical principles, even if these very principles need the "definitions" in question if we want to *test* them. The light principle, e.g., can only be empirically verified if we know how to measure the speed of light; and for this we need synchronized clocks. That Einstein was fully aware of this complication is already clear in the 1905 paper, but we find a more explicit discussion of this point and its relevance in the text of a lecture delivered by him in 1911 ([11]; [16], pp. 425–438).

This lecture, presented at a meeting of the *Naturforschende Gesellschaft Zürich*, gives a historical introduction to special relativity from the point of view of an experimentalist: centre stage is taken by the question of what can actually be measured and what the experimental support for the relativistic principles is. In connection with time this question becomes: How can we characterize time in such a way that we can actually measure it? The complication is in the determination of simultaneity, as Einstein explains ([16], p. 431): to synchronize clocks we need to know the speed of the signals by means of which we set these clocks with respect to each other, but this speed can in turn only be measured if we already have synchronized clocks at our disposal. This vicious measurement-circle makes it possible for us to make certain stipulations with regard to the speeds of signals, in particular the speed of light; and we use this to lay down that the speed of light in vacuum from A to B equals the speed from B to A. ("Wenn es nun aber ohne willkürliche Festsetzung prinzipiell ausgeschlossen ist, eine Geschwindigkeit, im speziellen die Geschwindigkeit des Lichts, zu messen, so sind wir berechtigt, bezüglich der Fortpflanzungsgeschwindigkeit des Lichtes noch willkürliche Festsetzungen zu machen. Wir setzen nun fest, dass die Fortpflanzungsgeschwindigkeit des Lichtes im Vacuum auf dem Wege von einem Punkt A nach einem Punkt B gleich gross sei wie die Fortplanzungsgeschwindigkeit eines Lichtstrahls von B nach A" ([16], 432).) With this, it becomes possible to unambiguously synchronize clocks: we have achieved a determination of time "from the standpoint of the measuring physicist" ("so haben wir eine Zeitbestimmung vom Standpunkt des messenden Physikers erlangt" ([16], 432)).

The text of this lecture is the one coming closest to the idea that relativistic simultaneity rests on an arbitrary definition; indeed, the word "arbitrary" ("willkürlich") occurs explicitly. But the context, the discussion of the possibilities of actual measurement, makes it clear that what is said here is only that simultaneity is not already determined, for the "measuring physicist", by the system of clocks at various places. This measuring physicist wants to have a concrete operational recipe for physical quantities, and for this something additional is needed. Once this lacuna is recognized, it is filled up immediately by Einstein by means of the light principle, without any discussion of possible alternatives. Seen this way, there is no conflict between the 1911 lecture text and the extensive analysis of the year before.

Putting all this evidence into one coherent whole, it is natural to conclude that Einstein's reference to "definitions", in his discussion of relativistic concepts, should not be taken as embodying a systematic operationalist or logical empiricist philosophy. There is a remarkable continuity and constancy in Einstein's utterances from the early twenties onwards, when he first explicitly addresses philosophical questions relating to space and time. In these philosophically inclined writings Einstein consistently rejects the project of defining concepts along the lines of operationalism or logical empiricism. The striking fact that Einstein uses the term "definition," in this very context of anti-operationalist reflections and much later than 1905, demonstrates that he did not realize the extent to which this term could excite philosophers and could give rise to misunderstandings. Actually, it is quite understandable that Einstein used the term "definition" in a way that did not fully accord with its use in logic or philosophy. Einstein's papers on special relativity, in which this term figures so prominently, are obviously *physics* papers, addressed to a physicist audience. In these papers Einstein was facing the task of convincing his readers that the spatiotemporal concepts of classical physics were not beyond discussion; what could be a better strategy to accomplish this aim than showing that actual measurements do not provide support for the applicability of these classical concepts? This strategy explains the emphasis on measurement procedures. In the rhetorical context it then is a natural step to reinforce the argument by speaking about the measurement procedures as "definitions" – a term that sounds stronger and more definitive than "measurement" or "determination".

Here it should be added that in spite of the fact that philosophically speaking the status of the meaning of spatial and temporal concepts is the same, Einstein in his 1905 paper only uses the term “definition” when he discusses the in his eyes problematical and to-be-changed concept of *time*. In the case of the spatial coordinates he simply speaks about “determining” or “measuring” the coordinates. Thus, in the beginning of Section 1, *Definition of Simultaneity*, Einstein writes [24, p. 277]: “Ruht ein materieller Punkt relativ zu diesem Koordinatensystem, so kann seine Lage relativ zu letzterem durch starre Maßstäbe unter Benutzung der Methoden der Euklidischen Geometrie *bestimmt* und in kartesischen Koordinaten ausgedrückt werden” (my emphasis). The translation by Perrett and Jeffery [17] renders this as: “If a material point is at rest relatively to this system of co-ordinates, its position can be *defined* relatively thereto by the employment of rigid standards of measurement and the methods of Euclidean geometry, and can be expressed in Cartesian co-ordinates” (my emphasis). In the context of the present discussion this translation is unfortunate. The German text does not speak about definitions: “Bestimmt” simply means “determined”, and does not possess the mathematical-logical-philosophical connotations of “defined”. Nevertheless, the translation cannot be called incorrect, since in physics the verb “to define” is frequently used in a loose manner, without its philosophical connotations. An example of this can be found in the 1905 special relativity paper itself. In the beginning of Section 2, *On the Relativity of Lengths and Times*, Einstein speaks about his two postulates and writes: “These two principles we *define* as follows” (my emphasis; original German: “. . ., welche beiden Prinzipien wir folgendermaßen definieren.”). Needless to say, the formulation of the postulates that follows this introductory sentence is not identical to the formulation Einstein gives of them in other places, even in the same article.

Summing up, there is every reason to believe that there was a considerable amount of constancy and coherence in Einstein’s thinking about geometrical concepts and that already in 1905 he was not really proposing to consider determinations by means of rods and clocks as strict definitions of space and time. In fact, it is almost self-evident that spatial and temporal concepts are more fundamental than the existence of rods and clocks: physics does not face any problems in describing imaginary worlds in which there are particles and fields in spatiotemporal configurations, but in which no rods and clocks can exist, not even in principle. Einstein can surely not have believed that space and time loose their meaning as soon as conditions become unfavourable to the existence of rods and clocks. Although the appeal to rods and clocks was well-advised from a strategic and rhetorical point of view, with the purpose of making it clear that classical concepts are not sacrosanct, at a fundamental level space and time should be discussed within the framework of their role in basic physical theory.

Einstein’s special theory of relativity served as a beacon for many twentieth-century philosophers of science; but many of them misinterpreted the philosophical implications of the theory (compare [15], for a similar thesis; see also [4], for an early discussion of a related theme). As Howard [15] points out, it was only with the downfall of logical empiricism, and the Quinean criticism of the analytic/synthetic distinction, that philosophy of science caught up with Einstein’s thinking about the status of physical concepts. In the philosophy of physics the notion that at the fundamental level it is basic physical theory that is important for the status of space and time, has only rather recently gained substantial ground (cf. [2, 3]). This testifies to the enormous force and persuasiveness of Einstein's rhetorical arguments involving rods and clocks. Nevertheless, the predominance of philosophical misinterpretations remains remarkable, given that an alternative presentation of special relativity has been available for a long time already in the work of Hermann Minkowski.

9.3 Minkowski's Analysis of Space and Time

On 21 September 1908 Minkowski [19] delivered his lecture *Raum und Zeit* (*Space and Time*, [17])[1]. The lecture quickly became exceptionally famous, and the passage from the introductory statement, "Henceforth space by itself and time by itself are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality," has become proverbial. Still, I believe that there are a number of aspects of Minkowski's ideas that so far have not received the attention they deserve. I shall here focus on two of them: the ontological status of Minkowski spacetime as a whole, and the meaning of spatiotemporal coordinates, respectively.

With regard to the first issue, I think that the impression created by Minkowski's just-quoted "winged words," namely that he insisted on considering spacetime as an entity existing independently of matter, is mistaken. Rather, examination of the text shows that Minkowski was close to Einstein's sympathies – although it should be borne in mind that Minkowski like Einstein was not explicit on his philosophy of space and time, writing as he was on physics and not on philosophy. Concerning the second issue (the meaning of spatiotemporal coordinates), it is well known that Minkowski did not engage in a discussion of rods and clocks. But exactly how he *did* propose to lay down these coordinates does not appear to have been the subject of serious study in the philosophy of physics literature. This is amazing, for as I shall argue Minkowski's proposed procedure is virtually identical to the procedure Einstein had in mind as fundamental in a future state of physical knowledge. Unlike Einstein, however, Minkowski was not deterred by the fact that he did not actually possess an adequate fundamental theoretical description of macroscopic space-time measuring devices (rods and clocks) and discussed the issue in an abstract way in terms of the form of the physical laws.

Minkowski's leading idea is to start with a theoretical account of elementary physical phenomena in terms of some arbitrary set of variables, then to perform mathematical transformations, and finally to introduce spacetime coordinates as that "system of reference x, y, z, t, space and time, by means of which these phenom-

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[1] Many of the ideas can already be found in a lecture Minkowski gave a year earlier (Minkowski, 1915).

ena then present themselves in agreement with definite laws." The "definite laws" Minkowski actually considered were those of Maxwell; but later in his article he assumes that *all* laws of nature, including those yet to be discovered and responsible for the stability of matter, should exhibit the same symmetry properties as the equations of electrodynamics. This procedure, relying as it is on very general symmetry features of the laws of nature, can be regarded as fulfilling Einstein's desiderata, in spite of the absence of complete knowledge of all specific laws and in spite of a lack of insight into how macroscopic measuring devices should be described by fundamental theory – as Minkowski's abstract and elegant mathematical treatment shows, such knowledge is not necessary to complete, albeit in a very abstract form, Einstein's programme.

In the Section 1 of his celebrated paper Minkowski introduces arbitrary coordinates in order to label events: *x, y, z, t*. A set of values of these coordinates represents a "world-point," and the manifold of *all* world-points is the "world." Minkowski makes it immediately clear, however, that he is not thinking of this manifold as an independent entity. First, he stresses that the coordinates are empirically accessible and always occur in union [17, p. 76]: "The objects of our perception invariably include places and times in combination. Nobody has ever noticed a place except at a time, or a time except at a place." Minkowski considers positions and times as attributes of physical, even "observable" ("*wahrnehmbarev*") things. The point is made very explicit a few lines further on, where Minkowski states: "Not to leave a yawning void anywhere, we will imagine that everywhere and everywhen there is something perceptible. To avoid saying "matter" or "electricity" I will use for this something the word "substance." The German original uses the term "*wahrnehmbar*" again: "Um nirgends eine gähnende Leere zu lassen, wollen wir uns vorstellen daß allerorten und zu jeder Zeit etwas Wahrnehmbares vorhanden ist" [19, p. 105]. The use of the term "observable" here may seem strange: Minkowski can hardly be supposed to require that miniscule portions of his substance, whatever its nature, should be accessible to the unaided senses. But we should bear in mind, again, that this is a science paper, not an exercise in philosophy – let alone an application of logical positivist ideas *avant la lettre*. Scientists very often use the term "observable" to denote things or states of affairs that they think are physically existing; things with which it is possible to enter into causal interaction and therefore "indirectly observable." It seems clear that Minkowski's "*wahrnehmbar*" should be interpreted in this vein, and simply should be taken as denoting "physical" or "material".

After his introduction of substantial points, Minkowski focuses attention on the career of one such point, for which he coins the term "worldline." He continues [17, p. 76]: "The whole universe is seen to resolve itself into such worldlines, and I would like to state immediately that in my opinion physical laws might find their most perfect expression as reciprocal relations between these worldlines." ("Die ganze Welt erscheint aufgelöst in solche Weltlinien, und ich möchte sogleich vorwegnehmen, daß meiner Meinung nach die physikalischen Gesetze ihren vollkommensten Ausdruck als Wechselbeziehungen unter diesen Weltlinien finden dürften.") Again, there is no indication here that Minkowski is thinking of his spacetime manifold as something that exists in itself, independently of its material "contents". Rather, his text breathes the atmosphere of Leibnizean, or perhaps rather Machian, relationism. It would not be very consistent, evidently, to capitalize on this point and now, suddenly, to see Minkowski in the role of a philosopher of science. Just as before, we have to read his article as a science text, in which philosophical notions are used in an intuitive and loose way.

Minkowski's view that the laws of physics represent relations between material worldlines is not incidental to his article, however: the idea plays a central role in his subsequent argument. Starting from the laws of physics, which express regularities in the behaviour of material systems, Minkowski starts an analysis from which his spacetime concepts are distilled: the coordinates x, y, z, t are found as those coordinates in terms of which the laws take on their standard forms. Everywhere in this analysis the coordinates refer to physical events, and the properties of spacetime emerge as the invariance properties of the pertinent physical laws. This approach is very different from the usual textbook approach, in which one begins with the symmetries of spacetime and then imposes these same symmetries on the physical laws. Minkowski's method does the opposite thing: one starts with physical systems and the regularities found in their behaviour, then formulates laws and studies the invariance properties of these laws and, finally, one calls the symmetries shared by all physical laws "spacetime" symmetries.

This is how Minkowski himself describes his procedure [17, p. 79]: "From the totality of natural phenomena it is possible, by successively enhanced approximations, to derive more and more exactly a system of reference x, y, z, t, space and time, by means of which these phenomena then present themselves in agreement with definite laws. But when this is done, this system of reference is by no means unequivocally determined by the phenomena. *It is still possible to make any change in the system of reference that is in conformity with the transformations of the group* G_c*, and leave the expression of the laws of nature unaltered*" (emphasis in the original). The group G_c is the proper Poincaré group, i.e., Lorentz boosts plus translations and rotations. Minkowski had introduced this group a little earlier in his paper, as a purely mathematical guess at a "natural" generalization of the Galilei group. In fact, one of the themes of Minkowski's paper is an ode to the power of pure mathematics to disclose facts about nature – he speculates about the possibility that special relativity could have been discovered by mathematical considerations alone. Possibly this song of praise for mathematics was partly motivated by Minkowski's wish to legitimate his "intrusion," as a mathematician, into a physical research area (cf. [26]). In other places of the paper Minkowski stresses the importance of empirical input, for instance in his famous opening sentence: "The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength." In the just-described procedure for defining space and time the starting point squarely lies in empirical data. But Minkowski's background as a mathematician remains clearly visible, especially in this prescription for finding inertial spacetime coordinates. Once the data about the relations between the phenomena are in, Minkowski tells us, a mathematical data analysis consisting in rewriting the equations in terms of different systems of independent variables, and successive approximations in order to finally find privileged systems of coordinates, suffices. I think it is not far-fetched to assume that it was exactly his abstract, mathematical, set of mind that made it possible for Minkowski to start with general properties of the physical laws and define spacetime coordinates on that basis. By contrast, Einstein's approach is more typical of the thinking of a working physicist, with a good deal of attention devoted to how spacetime coordinates are actually laid down in practice.

9.4 Intermezzo: Space-Time Coordinates as Physical Properties

According to Minkowski's proposal as explained above, we start with physical phenomena, study their relations, and derive the spacetime description from the resulting equations. In this whole procedure the spacetime coordinates function as attributes of physical systems or physical events, rather than as labels of points in an abstract spacetime manifold. In the context of particle mechanics this suggests treating space and time as physical quantities that have a similar status as mass, charge and similar particle properties. In other words, Minkowski's approach challenges us to think of space-time properties and space-time relations as inhering in physical systems and their relations, and not as referring to properties of an independently existing spacetime manifold (cf. [5, 25]).

The starting point of Minkowski's "successive approximation" method is that physical properties and relations can be quantified in infinitely many ways, depending on choices of scales and units. Given any such choice, the regularities in the dynamical behaviour of the particles assume a particular mathematical form. For example, if we connect particles by means of rods of position-dependent temperature, and express the forces between them in formulas that depend on the number of rods that fit between them (the "distance"), a complicated form of the laws of motion will result, very different from the standard Newtonian or special relativistic one. Conversely, if a standard form of the dynamical laws is given, this imposes restrictions on the way numerical values can be assigned to physical quantities. In particular, the standard position and time values fit in with the standard, inertial, form of the physical laws – with freedom associated with the invariance transformations of the set of equations. The inertial coordinates that emerge in this way are now not defined as markers identifying space-time points, but rather represent a particular way of quantifying space-time properties possessed by the physical systems. In this way of introducing coordinates no need arises to invoke the notion of spacetime as something additional to material systems.

The point deserves further discussion. Particles in classical physics are characterised by a number of intrinsic properties, like mass and electric charge, and by their state of motion. Mass and electromagnetic characteristics of particles are examples of *direct* properties [7]; they inhere in the particles without the need of any intermediary. By contrast, the positions of particles are traditionally viewed as *indirect*. That is, it is traditionally assumed that the geometric relations between the particles (how far apart they are from each other, what their relative orientation is, and so on) derive from the geometric relations between the *spatial points* they *occupy*. Accordingly, the geometric properties of the underlying space are considered as primary and the spatial relations between physical objects as secondary, indirect.

The way I read Minkowski, he proposes to assign space-time properties and space-time relations to particles in the same way as we assign mass values to them. Just as we do not suppose that there is an underlying substantive mass-space in which particles occupy points, we do not need the idea of a container space in which the particles are located. We can consider space-time properties as direct properties, whose introduction is justified by the possibility of formulating physical laws in terms of them. In the same way as mass values play a role in the formulation of regularities in the behaviour of particles, we can use (relative) positions, velocities and accelerations as quantities whose numerical values are needed to formulate laws of motion. As already pointed out, not all assignments of numerical values to the quantity "distance" will lead to the same form of the physical laws. If a preferred form of the laws of motion is specified, only a limited freedom in assigning position values is left.

The traditional objection against the idea that a substantive container space is superfluous is that relationist alternatives to mechanics will not be able to explain inertial effects, like those occurring in Newton's bucket. In those cases both classical and special relativistic mechanics makes a distinction between states of motion that are identical from a relationist point of view as they exhibit the same relative distances, relative velocities, etc., between the particles.

However, this difficulty is not insuperable. In fact, we now know there a purely relational version of classical mechanics exists, that may well be empirically adequate [18] – but it would be anachronistic to associate Minkowski's approach with this possibility. Rather, we should note that even in the context of ordinary classical and special relativistic mechanics it is possible to do justice to inertial effects and to make sense of acceleration without invoking an independent container space-time [5]. For take a way of assigning position and time coordinates such that the dynamics assumes its usual inertial form; if a particle has a non-vanishing second derivative of its position with respect to time *in these coordinates*, it is *accelerated* in the sense needed for the explanation of the bucket experiment and similar examples. Because the mathematical equations are exactly the same as in the usual accounts of mechanics, all the usual results can be reproduced: in particular, a system that is accelerated will evolve differently from a system that is unaccelerated, even if the relative distances and velocities are instantaneously the same. But again, in this approach we can do without an independent space. The distinction between the usual approach and the space-less approach is not in the formalism or in the predictions, but in the interpretation of the formalism. "Absolutely accelerated" in the scheme we are explaining does not mean, "accelerated with respect to absolute space", but rather "with non-vanishing second time derivative of the position according to a coordinate system scale in which the laws of motion have their standard form".

In order to treat time as a direct property as well, on a par with position, it is natural to focus on *events* as the fundamental physical objects with which physical quantities are to be associated. A particle event is assigned three position values (three components of the position) and a time value. As before, transforming these values can subsequently be used to find coordinates that lead to a preferred symmetrical of the dynamical equations.

The important difference between the relativistic and the Newtonian setting is that in relativity the symmetry transformations that leave the symmetric form of the equations invariant mix space and time quantities. What is invariant in special relativity is the *space-time interval* between two events, and relativistic particle dynamics can be formulated completely in terms of this four-dimensional distance. For example, the free motion of a particle is such that it makes the four-distance between the events in its existence a maximum. In the relativistic context the direct property view of space and time therefore assumes the following form. We start with particle events as our physical "objects"; they are assigned coordinates, i.e., four numbers x, y, z, t. These coordinates are then transformed in such a way that the relativistic equations of motions hold in their inertial form. This still leaves a lot of freedom, because the dynamics is invariant under the transformations of the Poincaré group. To make a connection with the conventional approach, one can think of these various assignments of position and time values as the result of applying standard measuring procedures from different inertial frames of reference.

The transition to relativity thus makes it possible to satisfy a traditional relationist desideratum, namely to make all quantities *relative*, in the sense of pertaining to relations between physical objects. However, the physical "objects" we are speaking about now, in the relativistic context, are particle events, and not the particles-at-the-same-time of Leibnizean relationism. This change of perspective results in a reconciliation between the relative character of the basic quantities, and the absoluteness of being accelerated. This is because Lorentz transformations not only leave the four-dimensional interval ds invariant, but also preserve the distinction between being accelerated and being in an inertial state of motion.

In the case of fields, instead of particles, there is the complication that fields seem to require the prior existence of the continuum of coordinate values for their very definition: fields are standardly defined via the assignment of field values to space-time points. Some authors (cf. [7]; ch. 8) take this to imply that field theories need an independently existing space-time manifold for their very possibility of existence: an assignment of properties to space-time points obviously requires the assumption that space-time points exist. However, this argument is inconclusive. Of course, *if* properties are indeed assigned to *space-time points*, the assumption is that there *are* such space-time points; this is tautological. The real question is whether the assignment of field values to x, y, z and t, without assuming anything beforehand about what these coordinates refer to, necessarily implies that they refer to independent space-time points. It seems obvious that the answer to this latter question is in the negative. If quantities are represented as functions of certain coordinates, it clearly does not follow that these coordinates refer to something real, existing independently of the things that are being coordinatized. The instance of colours and their mutual relations furnishes an example. Different colours and their shades can be represented in various ways; one way is as points on a three-dimensional colour solid. But the proposal to regard this "colour space" as something substantive, needed to ground the concept of colour, would be strange to say the very least. Of course, it is exactly the other way around: colours have certain relations among themselves, and their comparison makes it expedient to introduce the notion of a colour space. Coordinates are introduced to mathematically handle this ordering scheme, and to represent the colour relations. Exactly the same idea, transplanted to the context of space and time, lies at the basis of Minkowski's proposal: we start with physical systems and events, systematize their relations, and introduce space time coordinates to mathematically represent the result of this.

9.5 Simultaneity, Symmetries and Conventionality

We have seen that Einstein introduced his rule for establishing simultaneity with the term *definition*; this has been seized upon by many later philosophers of physics, to invoke Einstein's authority for the thesis that simultaneity in special relativity is conventional. Reichenbach [21] gave a systematic elaboration and explanation of this idea that has been very influential. The core of the conventionality doctrine is that local clock indications are objective because they consist in coincidences of material objects, like the coincidence of a pointer with a mark on a dial. These are things we can immediately observe and that do not depend on conventions (except in the trivial sense that we think up words to describe them, choose units in order to number the marks on the dial, and decide to fix our attention on these things in the first place). Whether or not the hands of a clock touch a certain mark on the clock's dial is something given by nature, and not determined by us. By contrast, simultaneity cannot be directly perceived: we need some rule to tell us how to establish simultaneity on the basis of observable facts, and it is only the stipulation of this rule that gives content to the concept. Such stipulations can be made in different ways, which gives rise to different but equivalent descriptions. The differences between these descriptions obviously are differences in judgments of simultaneity; the equivalence consists in the fact that the local states of affairs, the coincidences, remain the same in all of them. This epitomizes the philosophical, empiricist interpretation of Einstein's use of "definitions": local coincidences are objective facts, all the rest is a matter of choice. Of course, some choices may be simpler than others in the rules they use, or lead to simpler laws. But this can only yield a *pragmatic* argument for preferring one definition over another. Such pragmatic arguments relate to our interests and preferences, but not to truth. Thus, Reichenbach admits that the definition of simultaneity that makes the speed of light the same in all directions and leads to the standard form of Maxwell's equations is simpler for us, easier to remember and more readily applicable than alternatives. But according to Reichenbach that does not at all mean that these alternatives (with a value of ε unequal to ${}^{1}/{}_{2}$) have a lesser claim to being true. As long as the local facts remain the same, all theoretical schemes that accommodate them are equally true or false. Reichenbach does note that it is an objective fact that a choice of simultaneity that leads to isotropy of the speed of light is *possible*; but he emphasizes that still, it is our conventional choice to make use of this circumstance and set $\varepsilon = {}^1/_2$.

The conventionalist thesis thus depends on the notion that only local states of affairs are physically objective. For the logical empiricists this accorded with central tenets in their philosophy of science, because such local facts are paradigmatic of what is directly accessible to the senses. They were inspired by special relativity and Einstein's pronouncements; and indeed, as we have seen, Einstein himself made statements that appear to go into the same direction – in his explanation of what we have to understand by "time," Einstein starts with the uncontroversial local times indicated by clocks, and only subsequently "defines" a global time via his recipe for synchronizing clocks. But the appeal to Einstein's authority on this point is misdirected. As we have stressed before, there is every reason to suppose that Einstein did not intend his remarks as a consequence of a systematic empiricist philosophy of science, but rather as a stratagem employed to convince his readers that the temporal structure of the universe might be very different from that assumed in classical mechanics. Einstein wanted to make clear that on close inspection it turns out that there is no empirical support for the classical notion of absolute simultaneity. His target was not the uniqueness of the synchronization rule, but rather the tenability of the *classical* conception of time. Indeed, he never even considered using other definitions than his standard one for establishing simultaneity; and what is more, he directly linked this standard definition to the resulting form of the physical laws. In the beginning of Section 2 of his 1905 paper, when after the preliminary remarks of Section 1 he starts addressing the physical content of relativity theory, he again formulates his two basic principles, the relativity principle and the light principle. The latter is now formulated as: "Any ray of light moves in the 'stationary' system of co-ordinates with the determined velocity c, whether the ray be emitted by a stationary or by a moving body." Einstein immediately adds that in the definition of velocity, time must be taken in the sense of the definition of his Section 1. In other words, the way time has been defined in Section 1 of the 1905 paper is precisely such that the light principle receives its usual and natural form, with equal speed of light in all directions. Moreover, even *before* discussing the "meaning of time" in Section 1, Einstein had formulated the two relativity postulates in his Introduction, and had already worded his light postulate as the principle saying that light is always propagated in empty space with a definite velocity c, independent of the state of motion of the emitting body. This is about light in empty space (apart from the emitting body and the light itself), without any clocks, rods, and without signals going to and fro. The subsequent discussion in Section 1 has the purpose of making this postulate understandable and consistent with the other postulate. In other words, in Einstein's construction of the theory of special relativity the light postulate comes before the definition of time. Seen this way, Einstein's approach is similar in spirit to Minkowski's theory-centred one.

In contradistinction to Einstein, Minkowski explicitly states that he starts with physical theory in his construction of the spacetime manifold. The coordinates x, y, z, t are determined by Minkowski as the coordinates in terms of which the theory assumes a preferred form (namely the standard one, which among other things makes the speed of light isotropic). Of course, this physical theory is not given *a priori* to us. In his schematic description of his proposed procedure Minkowski explains that the theory should be distilled from regularities in the observed phenomena. That means that also Minkowski begins with local observations; but from the very start he takes into consideration what physical *relations* exist between these local phenomena, how they compare, and what regularities there are in the global pattern of local phenomena. Put differently, from the start Minkowski's approach includes *global* aspects of the situation: the spacetime coordinates that he constructs are sensitive to global properties of the pattern of events. This is especially true for the notion of simultaneity that follows from Minkowski's construction. Minkowski's simultaneity relation reflects the isotropy and homogeneity of spacetime, in the sense of the symmetry properties of the physical laws. As admitted even by Reichenbach, this isotropy and homogeneity is an objective physical *fact*: it proves possible, as an empirical result, to *find* a consistent description in which the laws display identical properties at all points in space and time, and in all directions (this is the description with $\varepsilon = {}^{1}/_{2}$). This existence claim is obviously not *a priori* true – in fact it is false in most general relativistic spacetimes. That it is true in special relativity tells us something objective and important about the nature of the continuum of events: it is highly symmetric. Standard simultaneity reflects this global symmetry by not only making the velocity of light a universal constant, but by making *all* fundamental physical processes that propagate in time position and direction independent.

So within the framework of Minkowski's approach standard simultaneity is not conventional but represents an objective physical fact. To some extent this argument was already anticipated by Reichenbach – and it seems that Reichenbach did not feel completely secure about whether Einstein was really behind the conventionality thesis. Indeed, apparently in order to dissociate himself from possible Einsteinian reservations on exactly this point, Reichenbach [21, p. 124] wrote: "Einstein immediately applied his solution of the problem of simultaneity to theoretical physics and for this reason the epistemological character of his discovery has never been clearly distinguished from the physical results. Therefore, we shall not follow the road taken by Einstein, which is closely connected with the principle of the constancy of the velocity of light, but begin with the epistemological problem."

It is exactly at this point that the misinterpretation of the philosophical message of special relativity begins to take concrete shape. Indeed, a couple of pages later, Reichenbach [21, p. 127] introduces his famous ε-formula, and after duly mentioning that only the value $\varepsilon = {}^{1}/_{2}$ was considered by Einstein, he continues: "*This definition* (i.e., with $\varepsilon = {}^{1}/_{2}$ – my addition) *is essential for the special theory of relativity*, but it is not epistemologically necessary. Einstein's definition, too, is just one possible definition" (emphasis added). So Reichenbach recognizes the essential role played by the standard notion of time in special relativity; but he denies that this special role has anything to do with objective facts of nature. Indeed, he goes on to state that Einstein's preference for $\varepsilon = {}^{1}/_{2}$ is solely based on the fact that this choice leads to simpler relations, and says: "It is clear that we are dealing here merely with descriptive simplicity, the nature of which will be explained in §27." Rather surprisingly, in §27 we find Reichenbach again emphasizing that a special definition of simultaneity is possible, precisely the one with $\varepsilon = {}^1/_2$, and that this special definition possesses important advantages because it makes the simultaneity relation symmetric and transitive. As Reichenbach stresses in the same passage, the existence of such a special definition is by no means self-evident but requires specific physical facts. That these requirements are indeed fulfilled in special relativity is what justifies Einstein's definition. But, Reichenbach continues [21, p. 168]: "This should not mislead us into believing that this definition is 'more true' because of its simplicity. Again we are concerned with nothing but descriptive simplicity." This is disappointing: we were promised an explanation of why $\varepsilon = {}^1/_2$ has only pragmatic virtues, which do not relate to truth; but here the earlier claim to that effect is just repeated. However, within the general context of Reichenbach's philosophy of science the motivation of the judgment is clear enough: for Reichenbach only local coincidences are objective building blocks of scientific theory, whereas the way we describe their correlations is conventional. Within this conceptual framework any advantage one global description possesses over another can necessarily only relate to pragmatic factors like simplicity, elegance, beauty, and so on.

The thesis defended by Reichenbach, and by many others in his wake, thus boils down to the following. There *are* global symmetries in Minkowski spacetime, and it *is* true that these are best represented by standard simultaneity (which is, of course, relative to a state of inertial motion). For example, the velocity of light will only conform to the symmetry and have the same value in all directions if we accept this standard simultaneity. But still, it is a conventional choice to *exploit* this possibility. But isn't this like saying that it is true that there are macroscopic objects in our world, that it is also true that this state of affairs is fittingly represented by a language that refers to these objects, but that it is still a matter of conventional choice to actually opt for such a language? In other words, is this conventionality not just the trivial conventionality that follows from the fact that *we* decide to use a language, that *we* coin words, and so on? Put differently again, is it not true that this kind of conventionality does not follow from the non-existence of relevant physical facts pertaining to simultaneity, but rather from a strategy that can be applied across the board and makes, if consistently employed, *every* physical concept conventional? As we have seen, in addition to local facts there exist *global* ones, as is admitted by all parties concerned. In special relativity there exist objective global spacetime symmetries, and it seems a highhanded measure to dismiss them as unimportant for the notion of simultaneity. If these global facts are taken into account, there is no reason to deem standard simultaneity in special relativity conventional (the situation is different in general relativity, or in accelerated frames of reference – indeed, in those contexts, in which there are no global symmetries, the case against the objectivity of global simultaneity becomes much stronger – see [6]).

Concluding, I think that Minkowski hit the nail on its head when he analysed space and time as implicitly defined by physical theory, and that by doing so he made explicit what was implicit in Einstein's original approach. If this is correct, it follows that neither from Einstein's nor from Minkowski's work support can be derived for the existence of the "epistemological revolution" that the logical empiricists perceived in relativity theory. In particular, the notorious conventionality thesis that was so ardently defended by many philosophical commentators on Einstein's revolution appears as a consequence of philosophical prejudices rather than as a part of relativity theory.

References

1. Bridgman, P.W.: 'Einstein's Theories and the Operational Point of View', pp. 333–355 in Schilpp (1949)
2. Brown, H.R.: Physical Relativity. Clarendon, Oxford (2005)
3. Dieks, D.: The "reality" of the Lorentz contraction. Zeitschrift für allgemeine Wissenschaftstheorie **15**, 33–45 (1984)
4. Dieks, D.: Gravitation as a universal force. Synthese **73**, 381–397 (1987)
5. Dieks, D.: Space and time in particle and field physics. Stud. Hist. Phil. Mod. Phys. **32**, 217–242 (2001)
6. Dieks, D.: Space, time and coordinates in a rotating world. In: Rizzi, G., Ruggiero, M.L. (eds.) Relativity in Rotating Frames, pp. 29–42. Kluwer, Dordrecht (2004)
7. Earman, J.: World Enough and Space Time. MIT Press, Cambridge, MA (1989)
8. Einstein, A.: Zur Elektrodynamik bewegter Körper. Annalen der Physik **17**, 891–921 (1905)
9. Einstein, A.: Über das Relativitätsprinzip und die aus demselben gezogen Folgerungen. Jahrbuch der Radioaktivität und Elektronik **4**, 411–462 (1907)
10. Einstein, A.: Le Principe de Relativité et ses Conséquences dans la Physique Moderne. Archives des sciences physiques et naturelles **29**, 5–28/125–144 (1910)
11. Einstein, A.: Die Relativitätstheorie. Naturforschende Gesellschaft in Zürich. Vierteljahrsschrift **56**, 1–14 (1911)
12. Einstein, A.: Geometrie und Erfahrung. Julius Springer, Berlin (1921)
13. Einstein, A.: Nichteuklidische Geometrie und Physik. Die neue Rundschau **1**, 16–20 (1925)
14. Einstein, A.: Ideas and Opinions. Crown Publishers, New York (1954)
15. Howard, D.: 'Einstein and the Development of Twentieth-Century Philosophy of Science', to appear in *The Cambridge Companion to Einstein* (2007)
16. Klein, M.J., Kox, A.J., Renn, J., Schulmann, R. (eds.): The Collected Papers of Albert Einstein, vol. 3. Princeton University Press, Princeton, NJ (1993)
17. Lorentz, H.A., Einstein, A., Minkowski, H., Weyl, H.: The Principle of Relativity. Methuen, London (1923) (First republished as a Dover edition in 1952, Dover, New York)
18. Lynden-Bell, D.: A relative Newtonian mechanics. In: Barbour, J., Pfister, H. (eds.) Mach's Principle from Newton's Bucket to Quantum Gravity, pp. 172–178. Birkhäuser, Basel (1995)
19. Minkowski, H.: Raum und Zeit. Physikalische Zeitschrift **10**, 104–111 (1909)
20. Reichenbach, H.: 'The Philosophical Significance of the Theory of Relativity', in Schilpp (1949), pp. 287–313 (1949)
21. Reichenbach, H.: The Philosophy of Space and Time. Dover, New York (1957) (Original German version: Philosophie der Raum-Zeit-Lehre. Walter de Gruyter, Berlin (1928))
22. Schlick, M.: Space and Time in Contemporary Physics. Oxford University Press, Oxford (1920) (Original German version: Raum und Zeit in der gegenwärtigen Physik. Julius Springer, Berlin (1917))
23. Schilpp, P.A. (ed.): Albert Einstein: Philosopher-Scientist. Open Court, La Salle (1949)
24. Stachel, J., Cassidy, D.C., Renn, J., Schulmann, R. (eds.): The Collected Papers of Albert Einstein, vol. 2. Princeton University Press, Princeton, NJ (1989)
25. Teller, P.: Space-time as a physical quantity. In: Achinstein, P., Kagon, R. (eds.) Kelvin's Baltimore Lectures and Modern Theoretical Physics. MIT Press, Cambridge, MA (1987)
26. Walter, S.: Minkowski, Mathematicians, and the Mathematical Theory of Relativity, pp. 45–86. In: Goenner, H., Renn, J., Ritter, J., Sauer, T. (eds.) The Expanding Worlds of General Relativity. Birkhäuser, Boston/Basel (1999)