Lorentz Contraction vs. Einstein Contraction. Reichenbach and the Philosophical Reception of Miller's Ether-Drift Experiments

Marco Giovanelli

Forum Scientiarum — Universität Tübingen,
Doblerstrasse 33 72074 Tübingen, Germany

marco.giovanelli@uni-tuebingen.de

In 1925 Reichenbach, by reacting to the positive result of Miller's ether-drift experiments, introduced a distinction between two types of rod contraction in special relativity: a kinematical 'Einstein contraction,' which depends on the definition of simultaneity, and a dynamical 'Lorentz contraction.' He argued that although both contractions happen to amount to the same Lorentz factor, they are conceptually different. In Reichenbach's view, only the 'Lorentz contraction' is at stake in the Michelson-Morley experiment. The arm of Michelson's interferometer is shorter than it would have been in classical mechanics in both Einstein and Lorentz's theories. In both theories, the Lorentz contraction requires an atomistic explanation based on a yet-unknown theory of matter. This paper concludes that Reichenbach's interpretation of special relativity shares features of the current neo-Lorentzian interpretations.

Keywords: Hans Reichenbach • Lorentz Contraction • Special Relativity • Neo-Lorentzian Interpretation

Introduction

The aspect of Reichenbach's interpretation of special relativity that has attracted the most attention is probably his famous conventionality of simultaneity—the freedom to choose which events are simultaneous in a given inertial frame depending on the value of the parameter ϵ. In a classical paper, David Malament (1977) has famously shown that one cannot allow such a freedom if one believes—as Reichenbach did—in the causal theory of time. Malament's paper, the epitome of an influential work, has generated an enormous amount of discussion (cf. Janis, 2014, sec. 4 for an overview).

More recently, however, Robert Rynasiewicz (2003) has, as far I can see, rightly challenged this view, showing that the non-standard definitions of simultaneity, though possible, play a "disappointingly little [role]" (Rynasiewicz, 2003, 125) in Reichenbach's formal construction (see also Rynasiewicz, 2012). The present paper intends to show that, whatever stance one might take about this matter, there is another aspect of Reichenbach's interpretation of special relativity that has gone unnoticed in recent literature, which is possibly more characteristic of his approach than the ϵ-definition of simultaneity: Reichenbach's distinction between two types of rod contractions occurring in special relativity, the Lorentz and Einstein contractions.

Reichenbach introduced this distinction introduced this distinction in his discussion of Miller's experiment. In 1925 the American experimentalist Dayton C. Miller (1925a) published the results of a series of Michelson-type experiments that he conducted at the top of Mount Wilson, in

Southern California. Miller's 'scandalous' detection of an ether-drift sparked, as one would expect, considerable debate that well beyond the physics community about a possible refutation of special relativity. The role of Miller experiment in the history of this experiment has been Einstein's attitude towards this experiment has been carefully investigated by Klaus Hentschel (1992). The debate that ensued in the physics community, in particular in the American one has been nicely presented by (Lalli, 2012). However, the philosophical reception of the experiment among 'philosophers' is still to be written. This paper will like to close this gap in the literature.

Reichenbach was the first to join the debate by publishing a paper the same year (Reichenbach, 1925), intending to demonstrate the physical implications of his axiomatization of special relativity. The peculiarity of Reichenbach's approach can be inferred from remarks that Moritz Schlick sent to Einstein at the end of 1925 (Schlick to Einstein, Dec. 27, 1925; EA, 21-591; cf. Hentschel, 1990, 361f.). To his surprise, Schlick found conclusions in Reichenbach's paper that could not have been further from his own. Reichenbach did not believe that the Lorentz contraction was an *ad hoc* hypothesis and that Einstein had dispelled (see Janssen, 2002, on this issue); he believed the contraction needed a dynamical explanation based on a theory of matter in special relativity, just like in Lorentz's theory. Thus Schlick realized that for Reichenbach there were no differences between Lorentz and Einstein's theories, and therefore no conventional choice between them. Moreover, the acceptance of Miller's results would not have implied a return to the old ether theory. By reading Schlick's letter, one is immediately disabused of the conviction that Reichenbach's axiomatization was a mathematically sophisticated version of Schlick's conventionalist reading of special relativity.

Reichenbach's line of argument was based on the above mentioned distinction between 'Lorentz contraction' and 'Einstein contraction,' which would resurface in his major 1928 monograph (Reichenbach, 1928). In a slightly updated parlance, one can say that the Lorentz contraction compares the proper length of a moving rod in special relativity with the length that the rod would have had in the classical theory; the Einstein contraction compares the proper length of a relativistic rod with its coordinate length in a moving frame. The first contraction implies a real difference and requires a molecular-atomistic explanation in both Einstein and Lorentz's theories. The second contraction is a perspectival difference that depends on the definition of simultaneity. Reichenbach holds the controversial opinion that only the first contraction is necessary to explain the Michelson experiment.

The aim of this paper to show how it was Reichenbach's reaction to Miller's experiment that prompted him to introduce this distinction. Section 1 of this paper presents a sketch of Reichenbach's axiomatization of special relativity, which is indispensable to understanding his line of argument. Section 2 introduces the distinction between Lorentz and Einstein contractions. Section 3 shows how Reichenbach uses the distinction to provide a philosophical account of Miller's experiment. Section 3 follows Reichenbach's 'geometrization' of the opposition between Lorentz/Einstein-contraction in terms of Minkowski diagrams, as presented in his 1928 book. The paper concluded by showing, that Reichenbach's distinction was resurrected by Adolf Grünbaum in the 1950s, that use it against Karl Popper's claim that the Lorentz contraction was not falsifiable.

Nevertheless, it was Reichenbach who must be credited for having attempted to show that the Lorentz-Einstein relationship should not be understood along the lines of the ad hoc/non ad-hoc distinction. According Reichenbach both theories attempt to account for an odd coincidence, that matter and fields contract in the same way (that is in Reichenbach's parlance the light geometry and matter geometry agree). Lorentz explained the difference as a deviation from a standard behavior for rods and clocks. Einstein, by contrast refused to give an explanation and simply declared that the relativistic behavior to be the natural behavior of rods and clocks. According to Reichenbach, however, an explanation is needed in Einstein theory as well. Surprisingly, in Reichenbach's view the explanation is not to be searched in the geometrical structure of space-time (Janssen, 2009), but in a theory of the material structure of rods and clocks. In this sense, Reichenbach approach appears as a curious anticipation of a neo-Lorentzian approach to special relativity Brown (2005).

1 Reichenbach's Axiomatization and the Role of the Michelson Experiment

On September 17, 1921 Reichenbach wrote to Moritz Schlick that in a few days he was going to present his project of an axiomatization of special relativity in Jena, at the meeting of the Association of the German Natural Scientists and Physicians (Reichenbach to Schlick, Sep. 17, 1921; SN). As he went on to explain to Einstein immediately thereafter, the main ambition of the project was to show that in special relativity "one can get along without rigid rods and material clocks" by using only light rays (Einstein to Reichenbach, Oct. 12, 1921; CPAE, Vol. 12, Doc. 266). Reichenbach's first sketch of his axiomatization project was published in the same year (Reichenbach, 1921). Reichenbach sent it to on at the beginning of 1922, warning that, although the paper was inspired by conventionalism, its results "reveals those facts that also conventionalism cannot interpret" (Reichenbach to Schlick, Jan. 18, 1922; SN); however Schlick was initially impressed that in Reichenbach's approach one could avoid the use not just of rods, but also clocks (Schlick to Reichenbach, Jan. 27, 1922; SN).

Reichenbach was moved by the conviction that complicated structures such as rods and clocks should be introduced at "the *end* of a physical theory, not at its beginning", since a "knowledge of their mechanisms presupposes a knowledge of the physical laws" (Reichenbach, 1922, 365; tr. 1978, 41) . Einstein also appreciated Reichenbach's efforts in this area (Einstein to Reichenbach, Mar. 27, 1922; CPAE, Vol. 13, Doc. 119). However, on May 10, 1922, Hermann Weyl alerted Reichenbach of major shortcomings in his approach: the class of inertial frames could not be singled out by using light rays alone (HR, 015-68-02). Reichenbach only papered over the cracks of Weyl's objection (Rynasiewicz, 2005) in the final version of his axiomatization, which was finished in March of 1923. After some difficulties finding a publisher, Reichenbach's monograph came out the following year (Reichenbach, 1924).

However, the book received a lukewarm, if even hostile reception. Schlick's student Edgar Zilsel reviewed the book positively for the *Die Naturwissenschaften* (Schlick to Reichenbach, May 7, 25; SN). However, he seemed to have considered Reichenbach's work simply a mathematically refined version of Schlick's conventionalism (Zilsel, 1925). However, it was in particular, a dismissive review by Weyl (1924), with whom Reichenbach had been on good terms, which clearly struck a hard blow. Reichenbach would still remember the episode with bitterness a decade later (Reichenbach to Einstein, Apr. 12, 1936; EA, 10-107). Thus it is unsurprising that Reichenbach rushed to defend his work. On July 28, 1925 the *Zeitschrift für Physik* received a paper from him, which was meant to clarify some technical issues with his project, and more importantly to plea for its philosophical relevance, to "expand upon those consequences which are especially important for physics" (Reichenbach, 1925, 32; tr. 2006, 171). The paper is relatively self-contained and provides a simplified presentation of Reichenbach's axiomatization, which we can roughly follow here (see Ryckman, 2005, sec. 4.4.2).

As is well known, Reichenbach's axiomatization differs from the typical 'deductive axiomatization' championed by, e.g., David Hilbert (Corry, 2004). In the latter, one sets an abstract general principle as an axiom, such as a variational principle (see Reichenbach, 1924, 2). Reichenbach, in contrast, put forward a 'constructive axiomatization.' As axioms he set empirical assertions capable of experimental verification. Reichenbach then derived the entire theory from them by integrating some additional conceptual elements, i.e., *definitions*. The definitions, a type he called 'coordinative definitions,' are arbitrary, thus neither true nor false. Einstein's famous definition of simultaneity is, in Reichenbach's view, a definition of this type. It amounts to the stipulation that when light signals are sent from a source to a mirror at relative rest and back again, the one-way time is $\epsilon = 1/2$ of the round-trip time. In principle, however, every value $0 < \epsilon < 1$ can be chosen.

Reichenbach's 'constructive axiomatization' consisted of ten axioms, five concerning the behavior of light (*Lichtaxiome* or light axioms, I-IV), and five concerning rods and clocks (*Körperaxiome* or matter axioms, VI-X).

- The *light axioms* define the equality of spatial and temporal distances for individual frames (*Lichtgeometrie* or light-geometry) using light rays alone. In Reichenbach's view the light axioms in special relativity do not differ from those in classical theory except for the assertion that the velocity of light is the velocity's upper limit. The relativistic light-geometry claims that light propagates in spherical waves in any uniformly moving system, whereas in the the classical light-geometry light propagates in spherical waves only in the ether system. The difference depends on the choice of ϵ, which is in principle arbitrary.
- The *matter axioms* postulate that material systems used as rods and clocks behave in accordance with the light geometry (*Körpergeometrie* or matter-geometry). Space distances and time intervals that are light-geometrically equal will also turn out to be equal if measured, respectively, with rigid rods and ideal clocks. Thus the content of special relativity can be expressed by saying that rods and clocks behave according to the relativistic light-geometry and not according to the classical one. In other terms, the Lorentz transformation, which leaves the spherical propagation of light invariant, turns out to be the transformation for measuring rods and clocks. If rods transformed according to the Galileian transformations, distances traveled by light in equal times would in general not be equal if measured by rods.

Thus, in Reichenbach's axiomatization, the matter axioms contained the part of relativity theory that can be tested empirically. The only relativistic axiom that was actually put to experimental verification, according to Reichenbach, was Axiom VIII: "Two intervals which are equal when measured by rigid rods, are also light-geometrically equal" (Reichenbach, 1924, 69; tr. 1969, 89). This amounts to nothing but an abstract formulation of the Michelson-Morley experiment. In an article published some months later (Reichenbach, 1926a), Reichenbach provided a good schematic description of Michelson's experimental setting (fig. 1), which we can roughly follow here.

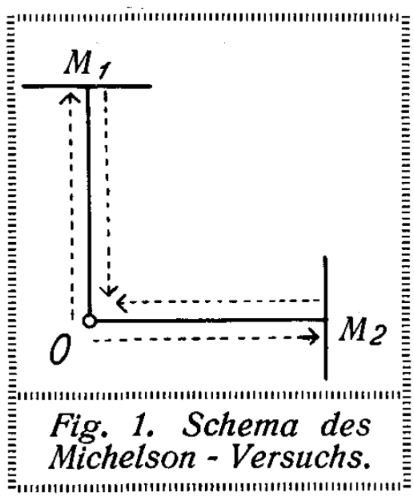


Figure 1: Reichenbach's stylized Michelson-Morley apparatus (from Reichenbach, 1926b, labels have been changed)

As is well known, the essential idea of the experiment was to split a beam of light at O, allow the two resultant beams to travel along two rigid rods placed at a right angle, with two mirrors M_1 and M_2 at the end points of the arm where the beams will be reflected back. The light beams are recombined at O to produce a series of interference fringes. What has to be experimentally tested is whether the travel time of a light signal going back and forth between two mirrors depends on whether the arms are parallel or perpendicular to the direction of motion. If the travel time along the two paths should change when the instrument is rotated, one should observe a shift of the interference fringes (Reichenbach, 1926b, 325; tr. 2006, 195f.).

According to the ether theory, the two light beams would return at the same time only if the apparatus is at rest with respect to the ether; but since the apparatus moves along with the Earth through space, the theory demands a deviation: the ray reaching M_2 must return slightly later, producing a change in the interference pattern. Thus, by measuring interference patterns, one could determine the state of motion of the Earth relative to the ether. In the 1880s Albert A. Michelson (1881), later with the assistance of Edward W. Morley (1887), showed that "in spite of the extreme precision of the measurement, there is no difference in the time to traverse either arm of the apparatus" (Reichenbach, 1926b, 326; tr. 2006, 195). At the turn of the century, "Morley and Miller [1905a,b] replicated this negative result in spite of the renewed increase in precision" (Reichenbach, 1926b, 326; tr. 2006, 195; translation modified).

How does one explain this negative result? Reichenbach told the following well-known story: "Lorentz in Leyden presented his explanation that assumed that all rigid bodies moving in opposition to the ether undergo a contraction" (Reichenbach, 1926b, 325; tr. 2006, 197). Lorentz justified the contraction hypothesis on the grounds that the molecular forces that hold material bodies together are of electromagnetic nature and are affected by translational motion. On the contrary, "in 1905, a more basic explanation was proposed by A. Einstein in which these contractions occur as a result of a universal principle, the principle of relativity" (Reichenbach, 1926b, 326; tr. 2006, 197). Thus Einstein could remain agnostic about the ultimate constitution of matter and only require the Lorentz covariance of all physical laws, including the unknown ones governing the material constitution of rods and clocks.

This, of course, can be cast in Reichenbach's own axiomatization, but as we shall see, this leads to some non-mainstream philosophical conclusions. Axiom VIII claims that two intervals OM_1 and OM_2 (fig. 1) are equal when measured in terms of the equality of the time intervals of the round trip of the light signals ($OM_1O = OM_2O$); then they are also equal when measured by rigid rods ($M_1 = M_2$). The Michelson experiment put to the test this correspondence postulated by axiom VIII, and the result was usually accepted as correct. In particular, it received further confirmation in the work of Rudolf Tomaschek (1924), an anti-relativist, who, inspired by Philipp Lenard, had repeated the experiment interferometer experiment using the light of fixed stars (Reichenbach, 1925, 39; tr. 2006, 180).

However, Reichenbach pointed out that "[r]ecently, doubts have been raised by Dayton C. Miller, who obtained a positive result on Mount Wilson" (Reichenbach, 1925, 39; tr. 2006, 180). If Miller's experiment were to be confirmed, then the round-trip times of the light signals along the two arms would become unequal ($OM_1O \neq OM_2O$). Therefore the matter-geometrical equality of distances would no longer coincide with the light-geometrical equality, and Axiom VIII would be disproved.

There was no agreement at the time on the reliability of Miller's results. Reichenbach, however, was quick to take advantage of the debate following the publication of Miller's paper, in order to convince the numerous skeptics of the physical implications of his axiomatization: "In this context, the axiomatization is proved to be extremely useful because it shows what particular role the Michelson experiment plays in the theory, what follows from it, and what is independent of it" (Reichenbach, 1925, 39; tr. 2006, 180).

2 Einstein Contraction vs. Lorentz Contraction: The First Appearance of Reichenbach's Distinction

Before entering into an analysis of Miller's experiment, Reichenbach made some remarks about the philosophical interpretation of special relativity, which, I think, are quite puzzling at first glance. Reichenbach warned his readers not to subscribe uncritically to a common interpretation of special relativity:

> [W]e should examine a particular error that has crept into the understanding of the theory of relativity. It concerns the problem of Lorentz contraction and thereby leads us to the Michelson experiment. One frequently hears the opinion expressed that in the Lorentzian explanation of the Michelson experiment the contraction of the arms of the apparatus is an '*ad hoc* hypothesis,' whereas Einstein explains it in a most natural way, namely, as a result of the relativization of the concept of simultaneity. But this is false. *The relativity of simultaneity has nothing to do with length contraction in the Michelson experiment.* That this opinion is false already follows from the fact that the contraction of one of the arms of the apparatus occurs precisely in the system in which the apparatus is at rest (Reichenbach, 1925, 43; tr. 2006, 187; my emphasis).

As we have mentioned, in order to explain the negative result of the Michelson experiment, Lorentz made the assumption that one arm of the apparatus is *contracted* by the amount $\sqrt{1 - v^2/c^2}$ when it moves relative to the ether. The theoretical asymmetry between the ether frame and those moving with respect to it is hidden from observation by a sort of universal conspiracy of nature. Einstein, on the contrary, considered both arms *equally long*, if measured at relative rest in the rest system, but one arm would appear contracted by the factor $\sqrt{1 - v^2/c^2}$ if measured from a moving system. In this way, the theoretical symmetry between the rest and moving system is reestablished. This of course was the consequence of the fact that the definition of the simultaneity of distant clocks using light signals is frame dependent. As any length measurement requires that both ends of the rod be measured at the same time, two observers in relative motion refer to something different when they talk about the length of the arm of the apparatus.

Reichenbach, however, explicitly rejected this standard interpretation, which he himself had defended not much earlier (Reichenbach, 1922). Let's take a look at Reichenbach's own explanation:

> That this opinion is false already follows from the fact that the contraction of one of the arms of the apparatus occurs precisely in the system in which the apparatus is at rest. The 'Einstein contraction' only explains that the arm is *shortened if it is measured from a different system.* But that does not explain the Michelson experiment. [The latter] proves that the rod lying in the direction of motion *is shorter when measured in the rest system than it should be according to the classical theory.* [...] [T]he Einsteinian theory, as well as Lorentz's, differs from the classical theory in asserting a measurably different effect on rigid rods that *has nothing to do with the definition of simultaneity* (Reichenbach, 1925, 43–44; tr. 2006, 187–188; translation modified; my emphasis).

Let's assume that there is a special ether system at absolute rest in which there are two equally long rigid rods, one of which behaves according to classical theory and the other to Einstein's theory; if we set the system in motion, then the two rods would cease to be equally long provided that they lie along the direction of the motion. The Lorentz-Einstein rod would be shorter than the classical rod. The difference could in principle be measured in the moving system itself as the difference between the rest-lengths of the classical and Lorentz-Einstein rods. Thus a comparison with length in another system is not at stake.

To avoid confusion, Reichenbach suggested that it is necessary to distinguish between: (a) the *Einstein contraction*, which results from the relativity of simultaneity and compares the length of the moving rod with the length of the rod at rest in the same Lorentz-Einstein theory; and (b) the *Lorentz contraction*, which compares the length of the same rod lying in the direction of motion in different theories—classical mechanics and the Lorentz-Einstein theory. In the classical theory the coordinate length of the moving rod is expected to be just as the coordinate length of the rod at rest. In the Lorentz-Einstein theory, by contrast, the coordinate length of a moving rod is always shorter than its proper length which is the same in all inertial frames. Nevertheless, Reichenbach claims, the proper length of a rod in motion can still be said to be shorter than the length that a classical rod would have if both were measured at relative rest in the moving frame (Giannoni, 1971).

Reichenbach uses the following notation. Let's call l a rod that behaves according to the Lorentz-Einstein theory and L a rod that behaves according to the classical theory. Let's label K the rest system and K' the moving system. The rest lengths of l and L in K are equal, or, as Reichenbach put it, $l_K^K = L_K^K$. In his notation the upper index refers to the system in which the rod is measured and the lower refers to the one in which the rod is at rest. Thus the rest-length of a moving rod from the perspective of a co-moving frame, in other terms its proper length, is $l_{K'}^{K'}$; the length of a rest-rod from the perspective of the moving frame $l_K^{K'}$ is its coordinate length.

Now let's consider what happens in the system K' that is in uniform motion with respect to K. The *Lorentz contraction* is concerned with the ratio $l_{K'}^{K'} : L_{K'}^{K'}$, whereas the Einstein contraction is concerned with the ratio $l_{K'}^{K} : l_K^K$. That is, the Lorentz contraction compares the behavior of the same rod in the Lorentz-Einstein and classical theories in the same inertial system K'. The *Einstein contraction* compares the behavior of two rods in the Lorentz-Einstein theory in different inertial systems, K and K'. The Einstein contraction depends on the relativity simultaneity and "is related to the comparison of *different magnitudes* within the *same theory*" (Reichenbach, 1925, 44; tr. 2006, 188) (coordinate and proper length). An analogous example would be the annual parallax, the difference in the position of a star as seen from two different extremes of the Earth's orbit. The Lorentz contraction is related to "the behavior of the *same magnitudes* according to *different theories*" (Reichenbach, 1925, 45; tr. 2006, 188) (the classical and relativistic proper length). An analogy to this would be the difference between the gravitational light deflection, which in general relativity is twice the Newtonian value.

According to Reichenbach, only the Lorentz contraction is at stake in the Michelson experiment, not the Einstein contraction: "It just happens that both contractions depend upon the same measurement factor $1/\sqrt{1-\vec{v}^2/c^2}$, and this is probably the reason why they are always confused with one another" (Reichenbach, 1925, 46; tr. 2006, 189). Reichenbach shows that the equality $l_{K'}^{K'} : L_{K'}^{K'} = l_{K'}^{K} : l_K^K$ is simply a consequence of the linearity of transformation. However, one should not miss the deep conceptual difference between the two contractions, which is hidden behind the coincidental numerical equality of the two factors (Reichenbach, 1925, 45f.; tr. 2006, 189f.). Thus in Reichenbach's view, it is not advisable to use the same expression 'contraction' in both cases.

It is this very expression 'contraction' that Reichenbach finds misleading. It implies that physical objects satisfy the classical theory without a cause, so that one must search for a cause for deviations from the correct behavior. However, there is no reason to see the classical theory as natural, and the Lorentz-Einstein theory as a distortion. The problem of causality should be posed in a different form; one must explain why measuring rods and clocks conform to a certain set of transformations defined in terms of the light-geometry and not to a different one. This causal problem is the same whether the rods and clocks behave according to the relativistic or classical transformation. In his 1924 monograph (Reichenbach, 1924, 70–71; tr. 1969, 90-91), we already find Reichenbach using Weyl's expression 'adjustment' as a good way to express this peculiar form of causality.

As Reichenbach explains, Weyl (1920) had introduced the expression 'adjustment' to account for the surprising behavior of the physical systems, such as atoms, that we use as rods and clocks. It cannot be a coincidence that atoms of the same type always have the same Bohr radius, independent of what happened to them in the past; this fact suggests that each time, they 'adjust' anew to a certain equilibrium value, rather then 'preserve' it. The analogy with special relativity seems to be the following: "*Einstein*'s idea can be formulated as meaning that *light geometry and matter geometry are identical*" (Reichenbach, 1924, 11; tr. 1969, 14). It is an odd coincidence that any physical system we use as a rod—whether it is made of steel, wood, etc.—always measures at equal lengths that are light-geometrically equal. "Light is a much simpler physical object than a material rod, and, when searching for a relation between the two, it should be initially supposed that it would not correspond to so ideal a scheme as the posited matter axioms" (Reichenbach, 1925, 47-48; tr. 2006, 95). This coincidence cries out for an explanation. However, the explanation should not account for the *divergence* from an alleged correct behavior, but a for the *convergence* toward a non-trivial one:

> The word adjustment, first used in this way by Weyl, is a very good characterization of the problem. [...] [A]ll metrical relations between material objects, including the observed fact of the Michelson experiment, must therefore be explained in terms of the particular way in which rigid rods adjust to the movement of light. Of course, the answer can only arise from a detailed theory of matter about which we have not the least idea [...] [.] The word 'adjustment' here thus only means a problem without providing an answer; the relevant fact is strictly formulated in the matter axioms without using the word 'adjustment.' Once we have this theory of matter, we can explain the metrical behavior of material objects; but at present the explanation from Einstein's theory is as poor as Lorentz's or the classical terminology (Reichenbach, 1925, 46–47; tr. 2006, 191).

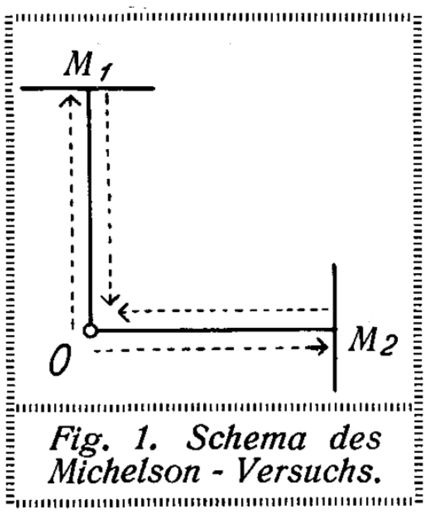


Figure 2: The Results of Miller's Experiment (from Reichenbach, 1926b)

According to Reichenbach, the difference between Lorentz and Einstein's theories is not in their empirical content, but in the types of explanation they provide. Both assert the facts encoded in axiom VIII, whereas the classical theory denies them. However, Lorentz's theory assumes the classical behavior of rods as 'self-evident,' so that any *deviation* from these relations must have a cause. Einstein's theory *renounces* the explanation and axiomatically *defines* two rods as equal if they behave in accordance with the Michelson experiment. "The superiority of Einstein's theory lies in the recognition of the epistemological legitimacy of this procedure" (Reichenbach, 1928, 233; tr. 1958, 202). However, according to Reichenbach, Einstein's agnosticism is unsatisfying. Without a suitable theory of matter describing those physical systems we happen to use as rods and clocks, Einstein's account of the metrical behavior of material objects is "just as poor as Lorentz's" (Reichenbach, 1925, 43; tr. 2006, 187).

3 Reichenbach on Miller's Experiment

After Reichenbach clarified the distinction between Lorentz and Einstein contraction, he could proceed further to show what would happen if a Michelson-type experiment gave a positive result.

As we have mentioned, in those years, raising this issue was more than just a mental exercise. A few months before the publication of Reichenbach's paper, Miller had published the result of his Mount Wilson experiments (Miller, 1925a).

Miller had begun working with Morley on the detection of the ether drift twenty years before, and they had published a null result (Morley and Miller, 1905a,b, 1907). The observations were made on slightly elevated locations and had indicated the occurrence of a small displacement. Miller conjectured it was significant. He remounted the Morley-Miller apparatus at a higher elevation at the Mount Wilson Observatory in 1921, moved it to Cleveland in 1922 (Miller, 1922), then back to Mount Wilson at 1734 metres above sea level in 1924. There Miller found a positive displacement of the interference fringes, approximately 10km/s, such as would be produced by a relative motion of the Earth and the ether (instead of the nearly 30 km/s expected). This suggested a partial drag of the ether by the Earth, which decreases with altitude (Miller, 1925a).

Miller's result immediately sparked considerable debate in the physics community. On May 23, 1926 the polish-born physicist Ludwik Silberstein (author of one the first special-relativistic textbooks) published an announce in *Nature* claiming that Miller's result refute special relativity and support Stokes-Planck theory based on the idea on a compressible ether (Silberstein, 1925). Arthur Stanley Eddington the major relativist in the English speaking world, replied on June 6, 1925 attacking Miller's result: if the ether drag depended on altitude, then also astronomical observations should be different on Mount Wilson respect to that on sea level (Eddington, 1925a).

A few week later, at the end of July, Reichenbach was the first 'philosopher' to attempt to participate to the debate, that he clearly saw as a good opportunity to convince the numerous skeptics of the validity of his axiomatic. Reichenbach's reaction reveals that the implications of Einstein's experiment were clearly non-mainstream:

> Now we can also address the question what would change in the theory of relativity if Miller's experiment were held to prove that the hitherto negative result of the Michelson experiment is in principle wrong. *Nothing would change* in Einstein's theory of time as it has nothing to do with the Michelson experiment. Also nothing would change with the light geometry; it remains in any case a possible definition for the space-time metric and probably a much better and more accurate one than the geometry of rigid rods and natural clocks. *But what would change is our knowledge about the adjustments of material things to the light geometry.* With respect to the matter axioms, as far as they differ from the classical theory, the Michelson experiment is the only one that has been confirmed. If this should be refuted, one has to develop a more complex view of the relationship between material objects and the light geometry (Reichenbach, 1925, 47; tr. 2006, 192; my emphasis).

In Reichenbach's axiomatization, the Michelson result is summarized in Axiom VIII. Thus, in the event that Miller's experimental results were not spurious, only this axiom would change. The principle of the constancy of the speed of light could be maintained, since it depends on a definition; thus one could construct a 'light geometry' using light signals but employing no rigid rods. "From this perspective, the Michelson experiment serves only as a bridge [Verbindungsgliedes] between the light geometry and the geometry of rigid rods" (Reichenbach, 1925, 327-328; tr. 2006, 203). If the experiment were rejected, this would only mean that "rigid rods do not after all possess the preferred properties that Einstein still attributes to them" (Reichenbach, 1925, 328; tr. 2006, 203). However, this would not imply a return to the old ether theory, but only a change in the matter axioms. Whereas the light axioms are completely certain, the matter axioms make statements about very complicated material structures. In Reichenbach's view they might have the "the validity of a first-order approximation in the same way that the ideal gas law cannot be maintained if the accuracy is increased" (Reichenbach, 1925, 48; tr. 2006, 192).

4 Schlick's Reaction to Reichenbach's Paper

Einstein drew very different consequences from Miller's experiment. Two days before Reichenbach's paper was submitted to the , on June 26, 1925, Edwin E. Slosson, the executive editor and director of the Science Service asked Einstein for a comment. Einstein's opinion at that time is clearly expressed by a letter sent a few days later to Robert A. Millikan, Caltech's 'chairman of the executive council': if the Miller's result turned out be correct, Einstein wrote, then "the whole theory of relativity would go down like a house of cards" (Einstein to Millikan, Jul. 13, 1925; EA, 17-357). A few days later, Einstein sent a very similar statement to Slosson which was published on *Science* on July 31, 1925. Against Silberstein's claim the Miller's results support the Planck-Stoke theory, Einstein argued that they would mean a return to Lorentz's theory: "No theory exists outside of the theory of relativity and the similar Lorentz theory which, except for the Miller experiment, explains all the known phenomena up to date" (Slosson, 1925).

In general however physicists expressed serious doubts, including Millikan and his group at Caltech (Epstein to Einstein, Jul. 25, 1925; EA, 10-565). Einstein himself, in spite of the openness that he showed in his public statement, was however not convinced at all that Miller's experiment was reliable. As, he wrote to Paul Ehrenfest in August 1925 "Auf das Miller-Experiment halte ich im Grund meiner schwarzen Seele nichts, nur darf ich es nicht laut sagen" (Einstein to Ehrenfest, Aug. 18, 1925; EA, 10-108). Einstein's skepticism, just like Eddington's, was motivated by the fact that a difference in height between Cleveland und Mount Wilson was not enough to explain Miller's results. In September 1925, Einstein suggested that a temperature difference (Einstein to Piccard, Sep. 21, 1925; EA, 19-211), and he communicated his results to Miller, who, by the end of the year, published a more detailed account of the experiment (Miller, 1925b).

In this context, it is not surprising that Reichenbach's quite different attitude towards Miller's results could appear puzzling. At the end of 1925, Schlick expressed disconcert in his correspondence with Einstein (Schlick to Einstein, Dec. 26, 1925; EA, 21-591). "Mr. Reichenbach" he wrote "has recently published a paper 'Über die physikalischen Konsequenzen der relativistischen Axiomatik' in the *Zeitschrift für Physik*"; Schlick was eager to know Einstein's opinion, since the paper "quite clearly shows the limit of the axiomatic method"weil sie ziemlich deutlich die Grenzen der axiomatischen Methode zu zeigen scheint (Schlick to Einstein, Dec. 26, 1925; EA, 21-591).

Schlick was understandably confused by Reichenbach's claim that the Lorentz contraction is not *ad hoc*; after all, this had been Schlick's reading of special relativity for at least a decade (Schlick, 1915). Actually Reichenbach's paper, by attacking a not further identified mainstream interpretation of special relativity, seems to have attacked more or less explicitly Schlick's interpretation. Schlick had still recently defended it at the Leipzig meeting *Gesellschaft Deutscher Naturforscher und Ärzte* to which Reichenbach also took part (Schlick, 1923). As is well known, Schlick considered Lorentz and Einstein's theory as empirically equivalent, that is equally consistent with all experiential data. However, whereas Lorentz theory introduces compensatory contractions and retardations, Einstein theory avoid the introduction of redundant elements, and it is thus preferable. Lorentz's theory, in Schlick's view, is analogous to the attempt of saving Euclidean geometry, by adding a force field deforming all measuring instruments. The difference is not a matter, of truth, but a matter of simplicity. As we as seen, within the Schlick's circle Reichenbach's axiomatic was initially received as a more sophisticated presentation of this point of view. However, Schlick now realized that Reichenbach had something very different in mind:

> The reflection on p. 43 [...] show in my opinion that his axiomatic cannot distinguish between special relativity and Lorentz's theory (with the contraction hypothesis) which seems to me obvious since the equations are the same. The real difference between the two theories is a philosophical one and cannot be grasped in the logical way of the axiomatic.

> This difference can be aptly expressed through the parlance that Reichenbach rejects. It is a an *ad hoc* hypothesis. Even if, from a logical point of view, spec. rel. theory must make as many assumptions as Lorentz's one. In the first case they ... in the framework of and the contraction hypothesis is psychologically really not *ad hoc*, while in the case of the Lorentz-Fitzgerald is a piece added *ad hoc*..

The limits of Reichenbach's approach, according to Schlick, emerge even more clearly from Reichenbach's reaction to Miller's experiment. If the experiment were to be confirmed, Schlick argued, the universal conspiracy of nature that hide the aether from detection would be broken and we had to return to the ether theory. By contrast, Reichenbach's Axiomatic method is incapable to grasp the difference between the two cases:

> Also the paper's remark—about the possible interpretation of Miller's experiments—does not seem to be to grasp the philosophical key point. If the experiments would really prove (and this is surely not the case), that a particular direction (that of the 'aether wind') were privileged, one would certainly abandon the relativistic physics; even if it were possible to keep relativity through the assumption of certain 'matter axioms,' one would certainly not take this path. Against this the axiomatic consideration remains indifferent. In the strict sense one cannot speak of physical consequences of the axiomatic. The question seems to me philosophically relevant, I would be deeply grateful if you could tell me in a few lines if I'm right.

Unfortunately, Einstein did not comply Schlick's request and he probably never read Reichenbach's paper. However, as we have seen, there is no doubt that Einstein's position was closer to that of Schlick.

Einstein had defined the contraction hypothesis as *ad hoc* (Einstein, 1908, 1915), provoking Lorentz's reaction Lorentz to Einstein, Jan. 23, 1915; CPAE, Vol. 8, Doc. 43. Also concering Miller's experiment, Einstein clearly agreed with Schlick (Hentschel, 1990, 361f.)). On January 19, 1926 a brief, but unequivocal statement of Einstein was published in the at that time most influential German newspaper, the *Vossiche Zeitung*: "If the results of Miller's experiments should indeed be confirmed, the relativity theory could not be upheld" (Einstein, 1926) . Einstein was clearly convinced the Miller's result were probably spurious, and he was ready to put money where its mouth was, as he explicitly phrase it (Einstein, 1926). However, he had no doubt that, if Miller's experiments turned out to be correct, the relativity principle would have to be abandoned entirely (Hentschel, 1992). This hardly surprising. In Einstein's view, the construction of a device detecting the ether-drift would have been comparable to the construction of a *perpetuum mobile* of the second kind þ. This the empirical principle on which the entire theory stands or falls.

A few months later, Reichenbach submitted a popular paper on the Miller's experiment entitled "Ist die Relativitätstheorie widerlegt?" which appeared in the weekly magazine *Die Umschau* on April 24, 1926. By that time, Reichenbach was fully aware of what "Einstein himself has recently said in the newspapers,"; however, he saw no reason to abandon his "less radical opinion" (Reichenbach, 1926b, 327; tr. 2006, 202), namely that "*Miller's result in no way affects the philosophical consequences of the theory of relativity*" (Reichenbach, 1926b, 328; tr. 2006, 203; my emphasis). It would only imply a change in our knowledge of the physical mechanism governing rods and clocks (Hentschel, 1982, 308).

Reichenbach too expressed some doubts about the correctness of Miller's experiment. The curve determined by Miller deviates from the expected symmetry with respect to the horizontal axis (fig. 2). J. Weber (1926) showed that Miller's figure omits some quite problematic measurement data without explanation. It was unlikely that on Mount Wilson, which after all is merely 0.03% of the Earth's radius, one would detect an ether wind 1/3 less than expected (Thirring, 1926). Moreover, Rudolf Tomaschek (1925, 1926), an anti-relativist, performed the so-called Röntgen-Eichenwald and Trouton-Noble experiments and obtained negative results on the *Jungfraujoch* in the Bernese Alps. Thus, it would have been interesting to replicate a Michelson-type experiment on the *Jungfraujoch* before drawing further conclusions.

However, the philosophical point of course lied elsewhere: "*What then does the theory of relativity have to infer from Miller's experiment?*" (Reichenbach, 1926b, 327; tr. 2006, 202). Concerning this point, Reichenbach was not afraid to express an opinion that radically differed from that of Einstein. Somehow anticipating his later famous distinction between the context of discovery and the context of justification, Reichenbach claimed that "[t]he Michelson experiment, of course, played a crucial role in the *historical development* of the theory" (Reichenbach, 1926b, 327; tr. 2006, 202; my emphasis)[1]; however, according to Reichenbach, "it does not occupy this same significant place in the relativistic theory's *logical structure*" (Reichenbach, 1926b, 327; tr. 2006, 202; my emphasis).

The logical structure of the theory was of course expressed by Reichenbach's own axiomatization:

> Under the ten axioms of the theory of relativity as I have laid them out, i.e., its ten most basic empirical propositions, there is only one that entails the Michelson result; it is only this axiom then that is thereby threatened. The principle of the constancy of the speed of light could be maintained in a more limited form even if the Michelson experiment's negative result were overturned. One could construct a 'light geometry' using light signals but employing no rigid rods to maintain a metrical understanding of the world and allow the previous formulation of all physical laws. From this perspective, the Michelson experiment serves only as a bridge between the light geometry and the geometry of rigid rods. Should this connection be lost, this would only mean that rigid rods do not after all possess the preferred properties that Einstein still attributes to them. This would not mean a return to the old aether theory, but rather a step towards the renunciation of a preferred system of measurement in nature (Reichenbach, 1926b, 327; tr. 2006, 203).

Even after a positive result of the aether-drift experiments, one could still maintain the light postulate, the claim that the motion of light is a spherical wave for any uniformly moving system, by adopting a non-standard definition of simultaneity. However equal lengths measured by rods and clocks would not be equal to equal lengths measured by light rays. Thus rods and clocks would adjust to the classical light geometry, and not to relativistic one.

Reichenbach, in his role of the defender of Einstein's theory, seems to have become more royal than the king. What Reichenbach probably meant, is that the real philosophical achievement of the theory is to have revealed a logical structure encoded in his axiomatization. Special relativity has disentangled conceptual elements, which in the classical theory appeared confused. There are empirical statements that serve as axioms (which can be true or false independently of it) and definitions (which are neither true nor false). Light axioms can be true or false, but simultaneity is a definition. In this sense Galilei and Lorentz transformations are neither true nor false, since both agree on the light axioms and are different because of definition of simultaneity (Reichenbach, 1926b). The matter axiom can be true or false since it is a matter if they adapt to Lorentz or to the Galilei transformations. This entire axiomatic structure, however, "is independent of specific, physical observations" (Reichenbach, 1926b, -NoValue-; tr. 2006, -NoValue-) 203][328]. In other terms, Miller's experiment, if confirmed would disprove axiom VIII, but would not engender the logical structure of Reichenbach's axiomatization. It is true that such logical structure has been derived "from a particular physical theory" (Reichenbach, 1926b, -NoValue-; tr. 2006, -NoValue-) namely special relativity, but the latter has "given rise to philosophical insights which no longer belong to the realm of physics but rather to the philosophy of nature" (Reichenbach, 1926b, -NoValue-; tr. 2006, -NoValue-) 204][328].

[1] This claim is actually problematic (cf., e.g., Stachel, 1982; Dongen, 2009).

In the meantime, Reichenbach thanks Max Planck's and and Max von Laue's support, had obtained the chair for natural philosophy in Berlin (Reichenbach to Schlick, Jul. 2, 1926; Schlick to Reichenbach, Jul. 5, 1926). Reichenbach clearly continued to consider the difference of this two types of contractions important. An entry in Rudolf Carnap diaries, that he met Reichenbach (near Berlin) on September 2, 1926: "He explained me the difference between Lorentz and Einstein contractions" (RC 025-72-05). Carnap had just joined the Schlick circle in Vienna. The philosophical disagreement between the Schlick-Circle and Reichenbach was deepening and went beyond the specific issue of the philosophical interpretation of special relativity. Reichenbach was convinced that the philosophy of nature should tackle metaphysical questions, such as that of the reality of the external world or of the human freedom (Reichenbach, 1926c). By contrast, Schlick, influenced by the young Carnap and Ludwig Wittgenstein deemed all such metaphysical questions as non-sensical (Schlick, 1926).

We do not know whether Reichenbach ever became aware of Schlick's negative opinion of his interpretation of special relativity. However he clearly did not made any conciliatory steps: Reichenbach's line of argument can be found again in the *Philosophie der Raum-Zeit-Lehre* (Reichenbach, 1928), which, as a letter from Reichenbach to Schlick reveals, was already finished at the end of 1926 (Reichenbach to Schlick, Dec. 6, 1926; SN), though Reichenbach was only able to find a publisher months later. When the book was finally published that the beginning of 1928 the importance of Miller's experiment was fading away especially in Germany. According to Reichenbach, "Michelson experiment has been confirmed to a very high degree" and he considered "this matter closed" (Reichenbach, 1928, 225; tr. 1958, 195). A similar opinion was expressed by Einstein in 1927 (Einstein, 1927). However Reichenbach still considered important to address "erroneous interpretations in the usual discussions on relativity" (Reichenbach, 1928, 225; tr. 1958, 195) that the discussion of Miller's experiment had revealed. In § 31 Reichenbach almost literally repeats the content of the 1925 paper we started with, as if the discussion of Miller's experiment would force him to clarify an central issue of his interpretation of special relativity. However, he also made some important clarifications. In particular he introduced his distinction between Lorentz and Einstein contraction in terms of Minkowski diagrams.

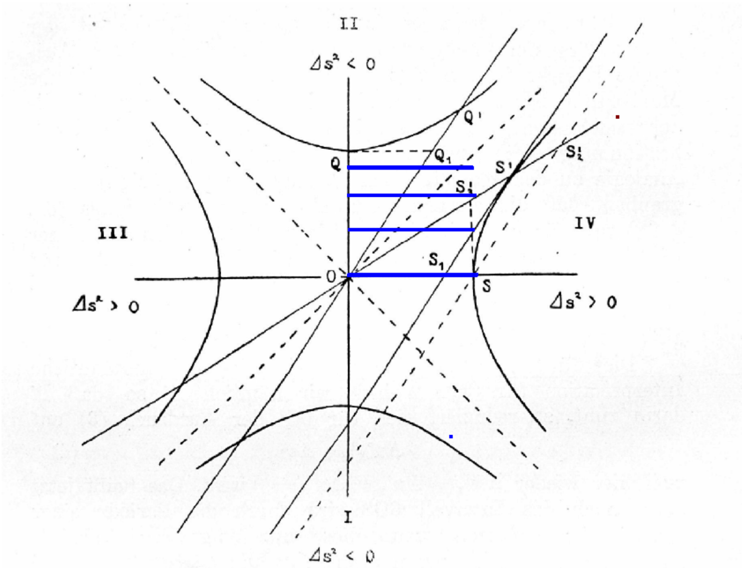
5 Lorentz Contraction vs. Einstein Contraction in Terms of Minkowski Diagrams

5.1 Minkowski Space-Time as a Graphical Representation

Reichenbach had a somewhat deflationary attitude towards Minkowski space-time. He viewed it as nothing but a 'graphical representation,' an expression he probably borrowed from Arthur Stanley Eddington (1925b). Reichenbach defines 'graphical representations' as structural analogies between different physical systems (e.g., compressed gases, electrical phenomena, mechanical forces, rigid bodies and light rays, etc.), which are realizations of the same conceptual system (e.g., the axioms of Euclidean geometry) (Reichenbach, 1928, 123ff; tr. 1958, 101ff).

In the case of Minkowski space-time, if "we speak of a geometrization of physical events, this phrase should not be understood in some mysterious sense; it refers to the identity of types of *structure* and not to the *identity of the coordinated physical elements*" (Reichenbach, 1928, 220; tr. 1958, 190). By asserting that measuring rods, clocks, and light rays behave according to the relations of congruence of the indefinite metric, Minkowski space-time provides the geometrical representation of the light and matter axioms. When in fig. 3 we 'symbolize,' say, the motion of rod OS with its rotation of the segment around O, "we only g[ive] a graphical representation, which means that the logical structure [*Beziehungsgefüge*] exhibited by the rods [...] [c]an also be realized by the space-time manifold" (Reichenbach, 1928, 220; tr. 1958, 190).

As Reichenbach put it, in Minkowski space-time a number Δs is coordinated to the coordinate differences $\Delta x_1, \ldots, \Delta x_4$ by means of the fundamental metrical formula $\Delta s^2 = \Delta x_1^2 + \Delta x_2^2 +$



Zur Realisierung der indefiniten Metrik durch Uhren und Maßstäbe.

Figure 3: Realization of the indefinite metric by means of light rays, clocks and measuring rods; from Reichenbach, 1928, 215; the label S_2 has been added

$\Delta x_3^2 - \Delta x_4^2$. The minus sign in the rule for computing real distances from coordinate distances is responsible for all the differences between the Minkowski and Euclidean geometry. The lines which are at a constant distance from the origin at Δs satisfy the equation $\Delta x^2 = \Delta x_1^2 - \Delta x_4^2$ rather than $\Delta x^2 = \Delta x_1^2 + \Delta x_4^2$. The contour lines are hyperbolae, and not circles like in Euclidean geometry. The four-hyperbolae in fig. 3, like the unit circle in Euclidean geometry, are the set of all points at $\Delta s = 1$ distance from O. The hyperbola $\Delta x^2 = 0$ degenerates into the two asymptotes, which group all other events in space-time into three different classes of intervals characterized by the sign of the quantity Δs^2. As one might expect, Reichenbach's next step is to find measuring instruments that behave like the indefinite type of metric, just like the behavior of the rods correspond to the definite one.

The physical realization of the negative Δs^2 is a physical object that satisfies the relations of congruence defined by the hyperbolas of quadrants I and II. The realization of the positive Δs^2 is a physical object that satisfies the relations of congruence defined by the hyperbolas of quadrants III and IV. The first is called a time-like interval $\Delta s^2 = -1$ and is realized by the proper time of a clock. The rotation of the interval OQ into the position OQ' represents a moving clock. $\Delta s^2 = 1$ is the space-like interval and is realized by the proper length of a rod. The rotation of interval OS into OS' sets the rod into motion. Light rays realize $\Delta s^2 = 0$, the limiting velocity, which cannot be reached but only approached arbitrarily closely. Otherwise rods and clocks behave by following the hyperbolic contour lines.

As Reichenbach rightly notices, there is a deep disanalogy between clocks and rods. Clocks are intrinsically four-dimensional measuring instruments, since they measure distances between two events. Measuring rods, on the other hand, are three-dimensional measuring instruments; they can be treated as four-dimensional instruments, if events are produced at their endpoints according to the appropriate definition of simultaneity (Reichenbach, 1928, 217; tr. 1958, 187). It is from this difference that all difficulties arise concerning the behavior of rods.

5.2 Lorentz vs. Einstein Contraction in Minkowski Space-Time

According to Reichenbach, resorting to the geometrical representation in fig. 3, one can easily recognize the difference between Lorentz and Einstein contraction. In Minkowski space-time the history of a uniformly moving unit rod is represented by a world-strip bounded by the parallel world-lines of the rod's endpoints. In the Lorentz-Einstein theory—keeping in mind that the points on the hyperbolas are at distance 1 from O—the moving rod is represented by the narrower strip between the world-lines OQ' and S_1S'; according to the classical theory it is represented by the wider strip between OQ' and SS'_2. The Einstein contraction maintains that the moving rod $OS' = 1$ looks shorter from the perspective of the rest frame (OS_1) than the proper length of the rod $OS = 1$ ($l^K_{K'} < l^K_K$). The Lorentz contraction refers to the fact that the classical length OS'_2 would be longer than the relativistic proper length $OS' = 1$, if both were measured in the same moving frame ($l^{K'}_{K'} < L^{K'}_{K'}$) (Reichenbach, 1928, 225; tr. 1958, 195).

"This assertion of the theory of relativity is based mainly on the Michelson experiment" (Reichenbach, 1928, 226; tr. 1958, 195). The Michelson experiment proves that material rods satisfy the light-geometrical definition of congruence in all inertial systems. The matter-geometrical equality of distances happens to coincide with the light-geometrical equality. In other terms, rods set in motion behave according to the hyperbolic contour lines in quadrant IV. Consider again fig. 1. OM_1 and OM_2 are regarded as equally long if light rays need equal time when they are sent back and forth along OM_1O and OM_2O. The negative result of the Michelson-Morley experiment establishes that if OM_1 and OM_2 are equally long if measured through light signals (in terms of the absence of interference fringes), then small measuring rods that are placed along the arms also mark off an equal number of segments on both arms:

$$(OM_1O = OM_2O) \rightarrow (OM_1 = OM_2) \tag{i}$$

According to the classical theory, the implication eq. i is satisfied only in the ether frame. In all other frames moving through the ether, the rest-length of the rod oriented in the direction of motion will no longer satisfy the implication eq. i. If OM_1 and OM_2 are the arms of the Michelson-Morley interferometer, then the fact that the matter-geometrical equality of distances does not coincide with the light-geometrical equality is revealed empirically by the shift in the patterns of light and darkness detected by the apparatus. The Lorentz-Einstein theory claims that the implication eq. i is satisfied in all frames; the light-geometrical distance always coincides with the matter-geometrical distance in all inertial systems. Light geometry is the same in both cases.

Thus, both Einstein and Lorentz's theories assume that the proper length of the arm of the Michelson apparatus lying in the direction of motion is shorter than it *would be* according to the classical theory. An objection that immediately comes to mind is that it is impossible to compare two magnitudes belonging to different theories, since there is no common standard of comparison. However, according to Reichenbach, his axiomatization provides the common standard: "In this case, the *tertium comparationis* is light, which in terms of light-geometrical definitions supplies a standard to which the rods of the different theories can be compared" (Reichenbach, 1928, 197; tr. 1958, 228). The hyperbola in quadrant IV (fig. 3) defines the distance 1 from O. Rods in motion, that is, rotated around O, follow the hyperbolas in the Lorentz-Einstein theory, but they do not do so in the classical theory. In this way, in Reichenbach's view, it is possible to compare rods I and L, though only one of them has an actual physical existence.

Thus, the Lorentz contraction is a *real difference*, just as the pressure of gas is really lower according to van der Waals equation than it would be according to the ideal gas equation. This does not mean that Einstein contraction is 'apparent.' Reichenbach prefers to speak of a *metrogenic* or (since motion is implied) metrokinematic difference: it depends on the fact that two observers in relative motion measure two different three-dimensional cross-sections of the world-strip of the rod; thus it is a 'perspectival difference' (Reichenbach, 1928, 228–229; tr. 1958, 197). The Michelson experiment implies a real difference between the classical theory and Einstein's theory, as well as between the classical theory and Lorentz's theory. But *there is no difference between Einstein's and Lorentz's theories*: "The concept of simultaneity does not enter into this problem at all" (Reichenbach, 1928, 229; tr. 1958, 198).

In geometrical terms, the Einstein contraction compares the width of different three-dimensional simultaneity cross-sections of the same relativistic world-strip (it is a perspectival difference); the Lorentz contraction compares the width of same three-dimensional cross-section of different world-strips (it is a real difference). Figure 3 reflects the fact that in the classical theory there is neither a Einstein nor a Lorentz contraction ($OS = OS_2 = OS_2'$). In the Lorentz-Einstein theory the Einstein contraction is Lorentz contraction ($OS_1' < OS_2' \rightarrow OS_1 < OS$). However, the two contractions are not identical.

This is essential to understand "[w]hat is the difference between Einstein's and Lorentz's theories" (Reichenbach, 1928, 229; tr. 1958, 198). In order to answer this question Reichenbach distinguishes between the following two statements (Reichenbach, 1928, 229; tr. 1958, 198):

1. the length of the moving rod $l^K_{K'}$ measured from the rest frame is different from its proper length l^K_K. As is well known, the proper length is greater than any coordinate length; the difference disappears only for the co-moving observer.

2. the rest-length of the moving rod $l^{K'}_{K'}$ is different from the rest-length of another rod $L^{K'}_{K'}$ which moves with it but satisfies the classical theory. The relativistic proper length in the moving frame is shorter than the classical length would be as judged from the same frame.

In Reichenbach's view, (b) can either be 'true' or 'false' in both Lorentz and Einstein's theories, depending on whether one accepts, say, Michelson or Miller's experimental results. In the geometrical representation, it is indicated by the difference between the distances $l^{K'}_{K'} = OS'$ and $L^{K'}_{K'} = OS'^2$ (fig. 3). On the contrary, (a) is neither 'true' nor 'false'; it depends on the definition of simultaneity adopted (one can choose the standard Einsteinian definition or an alternative one). In the geometrical representation, statement (a) is equivalent to the comparison of $l^K_K = OS$ and $l^K_{K'} = OS'$. Lorentz believed that lengths mentioned in (a) are different because the lengths mentioned in (b) are: the lengths of the arms of the interferometer are equally long only in the ether frame. On the contrary, Einstein declared the lengths mentioned in (a) are equal if measured at relative rest: the proper lengths of the arms of the interferometer are the same in all inertial frames (Reichenbach, 1928, 229–230; tr. 1958, 198–199). Reichenbach, however, made a further statement embodying the peculiarity of his approach: "*It is sometimes overlooked by proponents of the theory of relativity that statement (b) is nevertheless true*" (Reichenbach, 1928, 230; tr. 1958, 198) in Einstein's theory as well.

Thus Einstein's theory, just like Lorentz's, implies a contraction that is independent of the relativity of simultaneity, namely, the Lorentz contraction that implies a comparison of lengths $l^{K'}_{K'} < L^{K'}_{K'}$, i.e., $OS' < OS'^2$ in the same moving frame but in different theories. In addition, however, it contains the Einstein contraction, which compares lengths in the same theory: the proper length and the coordinate length $l^K_{K'} < l^K_K$, i.e., $OS < OS_1$. As we have seen, Reichenbach maintained the opinion that the two contractions only happen to amount to the same Lorentz factor as a consequence of the linearity of the Lorentz transformations. The *numerical identity* $OS_1 : OS = OS' : OS'^2$ is coincidental and it conceals a deeper *conceptual difference*.

Reichenbach repeats the proof of this statement, as it appeared in his 1925 article (Reichenbach, 1928, 230f.; tr. 1958, 199f.); however, in order to emphasize the difference between the two contractions, he constructs a counterexample in which an 'Einstein contraction' appears but there is no 'Lorentz contraction.' The example is based on the possibility of using Einstein's definition of simultaneity or an alternative one ($\epsilon \neq 1/2$) in the classical theory (Reichenbach, 1928, 231; tr. 1958, 200). Reichenbach's conclusion can be understood without entering into too much detail:

> The example [. . .] [m]akes it particularly clear that the Einstein contraction is a metrogenic phenomenon. In the geometrical representation this means that we may choose as the length of the rod differently directed sections through the world-strip of the rod. On the other hand, the geometrical representation of [fig. 3] shows very clearly that through the difference in the width of the strip, the Lorentz contraction indicates a difference in the actual behavior of the rod. These considerations also explain how it is possible to compare rods I and L, although only one of them is physically realized. OS is the same in both theories; the classical theory claims that the right-hand boundary of the strip parallel to OQ' must be drawn through S, whereas the new theory places the boundary along the tangent to the hyperbola which passes through S' (Reichenbach, 1928, 232; tr. 1958, 200).

Thus it is correct to claim that the Einstein contraction does not require any physical explanation; it is a metrogenic difference between proper and coordinate length. However, Lorentz's contraction *does* cry out for such an explanation. The negative result of the Michelson experiment implies that rods of all materials invariably behave in agreement with distances measured by light rays. How can such a coincidence be explained?

As we have seen, for Reichenbach, Weyl's expression 'adjustment' aptly expresses the need for an explanation, but it provides no details as to what it would look like. "The answer can of course be given only by a detailed theory of matter, of which we have not the least idea" (Reichenbach, 1928, 233; tr. 1958, 201; translation modified). It is important to emphasize that this is not a marginal aspect of Reichenbach's philosophy. According to Reichenbach the very same problem emerges in general relativity when the non-Euclidean nature of the continuum is taken into account. In this case, too, he resorts to the expression 'adjustment' and he refers his readers to the very same §31 of the book.

In general relativity measuring instruments in a gravitational field should also be considered 'free from deforming forces,' and not deviating from the Euclidean expected behavior; nevertheless one may still seek an explanation for why all measuring instruments happen to agree on the *same*, generally non-Euclidean, geometry. According to Reichenbach, in general relativity, too, only a theory of matter can explain this peculiar behavior of the space-time measuring instruments. In the presence of a real gravitational field it is impossible to arrange rods and clocks in a rectangular grid, just like it is impossible to 'develop' a flat piece of paper around a sphere. "We know that a more detailed investigation would reveal the presence of molecular force-fields, which affect the molecules on the surface of the sphere and thus force it into a definite" (Reichenbach, 1928, 295; tr. 1958, 258) congruence relationship.

Conclusion

The interest Miller's results in the faded away 1930s. The two great experimentalist of their time, Miller and Charles Edward St. John (St. John, 1932), discussed the issue the April 1930 at the NAS meeting (Lalli, 2012, 4.3). Miller replied defending his position Miller, 1933. However the Kennedy-Thordlike experiment Kennedy and Thorndike, 1932 settled the questioned, and special relativity was further confirmed by the Ives-Stilwell experiment (Ives and Stilwell, 1938, 1941) in spite of Charles Ives' intentions (Lalli, 2013). Miller results were considered inexplicable until in 1954, when Robert Shankland (1955), who also discussed the matter with Einstein (Shankland, 1963), put forward an explanation of Miller's data which is usually accepted, even if not universally (Lalli, 2012).

From the point of view of the history of philosophy of science, Miller's experiment played the role of a litmus test. It revealed how different was the conception of the relationship between special relativity and the Lorentz theory. Schlick reacted as expected rehearsing his conventionalist position. The difference between Lorentz and Einstein theory is conventional. The superiority of Einstein's theory is depend on the fact that the Einstein's theory entails less redundant elements, in particular no *ad hoc* molecular dynamical contraction of the rods. Reichenbach was forced to reveal some more striking consequences of his axiomatization program. By separating Einstein and Lorentz contraction, Reichenbach considered the contraction of rods regarded as a physically 'real' contraction, in the sense that in both theories rods behaves differently than in the classical theory. Einstein's and Lorentz's theories do not differ in this respect. In both cases a 'molecular' explanation of the contraction is needed. If Lorentz erroneously conceived of the explanation as a deviation caused by a force, Einstein proved negligent by avoiding any explanation. What has to be explained in not the reciprocal Einstein contraction, but the Lorentz contraction, that is the very fact that measurment made by material structures always agree with measurement made by light rays.

The distinction between two type of contractions, which is seldom mentioned in recent Reichenbach's scholarship, enjoyed renewed success in 1950s, just after Reichenbach's death in 1953. Adolf Grünbaum reintroduced it in a paper written in 1955 (Grünbaum, 1955). Grünbaum warned from a 'widespread error' to consider the 'the Lorentz-Fitzgerald contraction hypothesis was an *ad hoc* explanation,' and whereas Einstein that show it to be a consequence of the relativity of simultaneity. According to Grünbaum this "error is inspired by the numerical equality of the contraction factors of these two kinds of contraction" (Grünbaum, 1955, 460) . Both special relativity and Lorentz theory presupposes the Lorentz contraction: "using light as the standard for effecting the comparison, this hypothesis affirms that in the same system and under the same conditions of measurement, the metrical properties of the arm are different from the ones predicted by classical ether theory" (Grünbaum, 1955, 460) . This has nothing to do with a comparison of the length of the two arms in two different frames. Grünbaum mentions only at the end of the paper that his "treatment of several of the issues is greatly indebted to two outstanding works on the philosophy of relativity by Hans Reichenbach, which are not available in English" (Grünbaum, 1955, 460) .

The translation of Reichenbach's book was published (Reichenbach, 1958). A year later, the English translation (Popper, 1959) of Popper's *Logik der Forschung* (Popper, 1935) also appeared in print. Just thereafter, Grünbaum made implicit use of Reichenbach's account against Popper's claim that the Lorentz contraction is *ad hoc* Grünbaum (1959). In response to Popper, Grünbaum (1959) drew attention to the 1932 Kennedy-Thorndike experiment, which would disprove Lorentz contraction, if the theory is not supplemented with a clock retardation hypothesis. Grünbaum shows that this 'doubly-amended theory' can account for all optical experiments that supports special relativity, the Michelson- Morley experiment, the Kennedy-Thorndike experiment, and the Ives-Stillwell experiment. Further modifications can be introduced to account for electromagnetic kind of ether-drift experiments (Janssen, 1995). A few years later, Grünbaum implemented this line of reasoning his classical monograph on space and time *Philosophical Problems of Space and Time.* The distinction was also used by Carlo Giannoni (1971, 1978) and with a different nomenclature by Dennis Dieks (1984).

In Reichenbach's view both Lorentz and Einstein theory start with recognition of the odd coincidence that field geometry and matter geometry always agree. This odd coincidence requires an explanation. Lorentz theory, according to Reichenbach provided the wrong kind of explanation, however, Einstein's theory superficially got away without providing one. In the mainstream interpretation it was Minkowski that, so to say, provided the missing explanation, i.e. the geometrical structure space-time (Janssen, 2009). On the contrary, Reichenbach surprisingly adopted a sort of neo-Lorentzian approach (Brown, 2005), claiming the explanation should have been sought in a future theory of matter. The 'geometrical' explanation is rigid: a negative result of a Miller's experiment would have made the entire theory collapse, since the geometrical structure of space-time enters in the formulation of all laws of nature. The 'material' explanation is flexible: the laws of governing matter happen to agree with laws governing the fields, but do not need to do so. The positive result of an ether-drift experiment would have simply implied a readjustment in their reciprocal relationship. In this way, however, the 'material explanation' turns out to be simply the restatement of a matter of fact, that is no explanation at all.

Abbreviations

CPAE Albert Einstein (1987–). *The Collected Papers of Albert Einstein.* Ed. by John Stachel et al. 15 vols. Princeton: Princeton University Press, 1987–.

EA *The Albert Einstein Archives at the Hebrew University of Jerusalem.*

HR *Archives of Scientific Philosophy* (1891–1953). *The Hans Reichenbach Papers.* 1891–1953.

SN *Schlick Nachlass.* Noord-Hollands Archief, Haarlem.

References

Brown, Harvey R. (2005). *Physical Relativity. Space-time Structure from a Dynamical Perspective.* Oxford: Clarendon, 2005.

Corry, Leo (2004). *David Hilbert and the Axiomatization of Physics (1898-1918). From* Grundlagen der Geometrie *to* Grundlagen der Physik. Dordrecht: Kluwer, 2004.

Dieks, Dennis (1984). "The 'Reality' of the Lorentz Contraction." *Zeitschrift für allgemeine Wissenschaftstheorie* 15, 330–342.

Dongen, Jeroen van (2009). "On the Role of the Michelson-Morley Experiment: Einstein in Chicago." *Archive for History of Exact Sciences* 63, 655–663.

Eddington, Arthur Stanley (1923). *The Mathematical Theory of Relativity.* Cambridge: University Press, 1923.

— (1925a). "Ether-drift and the Relativity Theory." *Nature* 115, 870.

— (1925b). *Relativitätstheorie in mathematischer Behandlung.* Mit einem Anhang "Eddingtons Theorie und Hamiltonsches Prinzip" von Albert Einstein. Trans. by Alexander Ostrowski and Harry Schmidt. Berlin: Springer, 1925. German translation of Eddington, 1923.

Einstein, Albert (1908). "Relativitätsprinzip und die aus demselben gezogenen Folgerungen." *Jahrbuch der Radioaktivität und Elektronik* 4, 411–462. Repr. in CPAE, Vol. 2, Doc. 47.

— (1915). *Die Relativitätstheorie.* In: *Die Kultur der Gegenwart. Ihre Entwicklung und ihre Ziele.* Ed. by Paul Hinneberg. Leipzig: Teubner, 1915, Part 3, Sec. 1, Vol. 3: *Physik.* Ed. by Emil Warburg, 703–713. Repr. in CPAE, Vol. 4, Doc. 21.

— (1925). "Eddingtons Theorie und Hamiltonsches Prinzip." In: Eddington, Arthur Stanley. *Relativitätstheorie in mathematischer Behandlung.* Mit einem Anhang "Eddingtons Theorie und Hamiltonsches Prinzip" von Albert Einstein. Trans. by Alexander Ostrowski and Harry Schmidt. Berlin: Springer, 1925. Repr. in CPAE, Vol. 14, Doc. 282.

— (1926). "Meine Theorie und Millers Versuche." *Vossiche Zeitung.* 1926. Repr. in CPAE, Vol. 15, Doc. 161.

— (1927). "Neue Experimente über den Einfluß der Erdbewegung auf die Lichtgeschwindigkeit relativ zur Erde." *Forschungen und Fortschritte* 3, 36–37.

Giannoni, Carlo (1971). *Einstein and the Lorentz-Poincaré Theory of Relativity.* Proceedings of the 1970 Biennial Meeting Philosophy of Science Association. In: *PSA 1970. In Memory of Rudolf Carnap.* Ed. by Roger C. Buck and Robert S. Cohen. Dordrecht: Reidel, 1971, 575–589.

— (1978). "Relativistic Mechanics and Electrodynamics without One-way Velocity Assumptions." *Philosophy of Science* 45, 17–46.

Grünbaum, Adolf (1955). "Logical and Philosophical Foundations of the Special Theory of Relativity." *American Journal of Physics* 23, 450–464.

— (1959). "The Falsifiability of the Lorentz-Fitzgerald Contraction Hypothesis." *The British Journal for the Philosophy of Science* 10, 48–50.

— (1963). *Philosophical Problems of Space and Time.* Dordrecht, Boston/London: Reidel, 1963.

Hentschel, Klaus (1982). "Zur Rolle Hans Reichenbachs in den Debatten um die Relativitätstheorie (mit der vollständigen Korrespondenz Reichenbach-Friedrich Adler im Anhang)." *Nachrichtenblatt der Deutschen Gesellschaft für Geschichte der Medizin, Naturwissenschaft & Technik* 3, 295–324.

Hentschel, Klaus (1990). *Interpretationen und Fehlinterpretationen der speziellen und der allgemeinen Relativitätstheorie durch Zeitgenossen Albert Einsteins*. Basel et al.: Birkhäuser, 1990.

— (1992). "Einstein's Attitude Towards Experiments. Testing Relativity Theory 1907–1927." *Studies in History and Philosophy of Science* 23, 593–624.

Ives, Herbert E. and G. R. Stilwell (1938). "An Experimental Study of the Rate of a Moving Atomic Clock." *Journal of the Optical Society of America* 28, 215–226.

— (1941). "An Experimental Study of the Rate of a Moving Atomic Clock II." *Journal of the Optical Society of America* 31, 369.

Janis, Allen (2014). *Conventionality of Simultaneity*. In: *Stanford Encyclopedia of Philosophy*. Ed. by Edward N. Zalta. Fall. 2014.

Janssen, Michel (1995). "A Comparison between Lorentz's Ether Theory and Special Relativity in the Light of the Experiments of Trouton and Noble." PhD thesis. University of Pittsburgh, 1995.

— (2002). "Reconsidering a Scientific Revolution. The Case of Einstein Versus Lorentz." *Physics in Perspective* 4, 421–446.

— (2009). "Drawing the Line between Kinematics and Dynamics in Special Relativity." *Studies in History and Philosophy of Science. Part B: Studies in History and Philosophy of Modern Physics* 40, 26–52.

Kennedy, Roy J. and Edward M. Thorndike (1932). "Experimental Establishment of the Relativity of Time." *Physical Review* 42, 400–418.

Lalli, Roberto (2012). "The Reception of Miller's Ether-drift Experiments in the USA." *Annals of Science* 69, 153–214.

— (2013). "Anti-relativity in Action. The Scientific Activity of Herbert E. Ives between 1937 and 1953." *Historical Studies in the Natural Sciences* 43, 41–104.

Malament, David (1977). "Causal Theories of Time and the Conventionality of Simultaneity." *Nous* 11, 293–300.

Michelson, Albert A. (1881). "The Relative Motion of the Earth and the Luminiferous Ether." *American Journal of Science* 22, 120–129.

Michelson, Albert A. and Edward W. Morley (1887). "On the Relative Motion of the Earth and the Luminiferous Ether." *American Journal of Science* 34, 333–345.

Miller, Dayton C. (1922). "Ether-Drift Experiments at Mount Wilson in 1921 and at Cleveland in 1922." *Science* 55, 496.

— (1925a). "Ether-Drift Experiments at Mount Wilson." *Proceedings of the National Academy of Sciences of the United States of America* 11, 306–314.

— (1925b). "Report on Ether Drift Experiments." *Annual Report of the National Academy of Sciences*, 48–49.

— (1933). "The Ether-Drift Experiment and the Determination of the Absolute Motion of the Earth." *Review of Modern Physics* 5, 203–242.

Morley, Edward W. and Dayton C. Miller (1905a). "On the Theory of Experiments to detect Aberrations of the Second Degree." *Philosophical Magazine* 9-6th Series, 669–680.

— (1905b). "Report of an Experiment to Detect the Fitzgerald-Lorentz Effect." *Proceedings of the American Academy of Arts and Sciences* 61, 321–328.

— (1907). "final Report on Ether-Drift Experiments." *Science* 25, 525.

Popper, Karl R. (1935). *Logik der Forschung. Zur Erkenntnistheorie der Modernen Naturwissenschaft*. Berlin: Springer, 1935.

— (1959). *The Logic of Scientific Discovery*. New York: Basic Books, 1959.

Reichenbach, Hans (1921). "Bericht über eine Axiomatik der Einsteinschen Raum-Zeit-Lehre." *Physikalische Zeitschrift* 22, 683–687.

— (1922). "La signification philosophique de la théorie de la relativité." *Revue philosophique de la France et de l'étranger* 93, 5–61.

— (1924). *Axiomatik der relativistischen Raum-Zeit-Lehre*. Vieweg: Braunschweig, 1924. Repr. in Reichenbach, 1977, Vol. 3, 3–171.

— (1925). "Über die physikalischen Konsequenzen der relativistischen Axiomatik." *Zeitschrift für Physik* 34, 32–48. Repr. in Reichenbach, 1977, Vol. 3, 172–183.

— (1926a). "Die Probleme der modernen Physik." *Die Neue Rundschau*. 1926.

— (1926b). "Ist die Relativitätstheorie widerlegt?" *Die Umschau* 30, 325–328.

— (1926c). "Metaphysik und Naturwissenschaft." *Symposion* 1, 158–176.

— (1928). *Philosophie der Raum-Zeit-Lehre*. Berlin/Leipzig: Walter de Gruyter, 1928. Repr. in Reichenbach, 1977, Vol. 2.

— (1958). *The Philosophy of Space and Time*. Ed. by Maria Reichenbach. Trans. by Maria Reichenbach and John Freund. New York: Dover Publ., 1958.

— (1969). *Axiomatization of the Theory of Relativity*. Ed. and trans. by Maria Reichenbach. With a forew. by Wesley C. Salmon. Berkeley: University of California Press, 1969.

— (1977). *Gesammelte Werke in 9 Bänden*. Ed. by Andreas Kamlah and Maria Reichenbach. Braunschweig/ Wiesbaden: Vieweg, 1977.

— (1978). *Selected Writings. 1909–1953*. Ed. and trans. by Maria Reichenbach. Dordrecht: Reidel, 1978.

Reichenbach, Hans (2006). *Defending Einstein. Hans Reichenbach's Writings on Space, Time, and Motion.* Ed. by Steven Gimbel and Anke Walz. Cambridge et al.: Cambridge University Press, 2006.
Ryckman, Thomas (2005). *The Reign of Relativity. Philosophy in Physics 1915-1925.* Oxford/New York: Oxford University Press, 2005.
Rynasiewicz, Robert (2003). *Reichenbach's ϵ-definition of Simultaneity in Historical and Philosophical Pespective. Re-evaluation and Future Perspectives.* In: *The Vienna Circle and Logical Empiricism.* Ed. by Friedrich Stadler. Dordrecht: Springer, 2003, 121–129.
— (2005). "Weyl vs. Reichenbach on *Lichtgeometrie*." In: *The Universe of General Relativity.* Ed. by A. J. Kox and Jean Eisenstaedt. Boston: Birkhäuser, 2005, 137–156.
— (2012). "Simultaneity, Convention, and Gauge Freedom." *Studies in History and Philosophy of Science. Part B: Studies in History and Philosophy of Modern Physics* 43, 90–94.
Schlick, Moritz (1915). "Die philosophische Bedeutung des Relativitätsprinzips." *Zeitschrift für Philosophie und philosophische Kritik* 159, 129–175.
— (1923). *Die Relativitäatstheorie in der Philosophie.* In: *Verhandlungen der Gesellschaft Deutscher Naturforscher und Ärzte.* 87. Versammlung zu Leipzig, Hundertjahrfeier vom 17. bis 24. September 1922. Ed. by Alexander Wittig. Leipzig: Voge, 1923, 58–69. Repr. in Schlick, 2006, Vol. 1.5, 529–547.
— (1926). "Erleben, Erkennen, Metaphysik." *Kant-Studien* 31, 146–158.
— (2006). *Gesamtausgabe.* Ed. by Friedrich Stadler and Hans Jürgen Wendel. Berlin: Springer, 2006.
Shankland, Robert S. (1963). "Conversations with Albert Einstein." *American Journal of Physics* 31, 47–57.
Shankland, Robert S. et al. (1955). "New Analysis of the Interferometer Observations of Dayton C. Miller." *Reviews of Modern Physics* 27, 167–178.
Silberstein, Ludwik (1925). "D. C. Miller's Recent Experiments, and the Relativity Theory." *Nature* 115, 798–799.
Slosson, Edwin E. (1925). "The Relativity Theory and the Ether Drift." *Science* 62, viii.
St. John, Charles Edward (1932). "Observational Basis of General Relativity." *Publications of the Astronomical Society of the Pacific* 44, 277.
Stachel, John (1982). "Einstein and Michelson. The Context of Discovery and the Context of Justification." *Astronomische Nachrichten* 303, 47–53. Repr. in Stachel, 2002, 177–190.
— (2002). *Einstein from 'B' to 'Z'.* Boston: Birkhäuser, 2002.
Thirring, Hans (1926). "Prof. Miller's Ether Drift Experiments." *Nature* 118, 81–82.
Tomaschek, Rudolf (1924). "Über das Verhalten des Lichtes außerirdischer Lichtquellen." *Annalen der Physik.* 4th ser. 378, 105–126.
— (1925). "Über Versuche zur Auffindung elektrodynamischer Wirkungen der Erdbewegung in großen Höhen II." *Annalen der Physik.* 4th ser. 78, 743–756.
— (1926). "Über Versuche zur Auffindung elektrodynamischer Wirkungen der Erdbewegung in großen Höhen II." *Annalen der Physik.* 4th ser. 80, 509–514.
Weber, J. (1926). "Der Michelsonversuch von D. C. Miller auf dem Mount Wilson." *Physikalische Zeitschrift* 27, 5–8.
Weyl, Hermann (1920). "Elektrizität und Gravitation." *Physikalische Zeitschrift* 21, 649–650. Repr. in Weyl, 1968, Vol. 2, Doc. 40.
— (1924). "Review of Reichenbach, *Axiomatik der relativistischen Raum-Zeit-Lehre* [Reichenbach, 1924]." *Deutsche Literaturzeitung* 45, 2122–2128.
— (1968). *Gesammelte Abhandlungen.* Ed. by Komaravolu Chandrasekharan. 4 vols. Berlin: Springer, 1968.
Zilsel, Edgar (1925). "Review of Reichenbach, *Axiomatik der relativistischen Raum-Zeit-Lehre* [Reichenbach, 1924]." *Die Naturwissenschaften* 13, 407–409.