



# Can we trust Einstein's accounts of the genesis of special relativity?

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CAN WE TRUST EINSTEIN'S ACCOUNTS  
OF THE GENESIS OF SPECIAL RELATIVITY?

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*Summary:* There are three kinds of sources available to reconstruct the reflections that led Einstein to special relativity: a few contemporary letters and documents, his impersonal accounts of the genesis of this theory, and recollections of his own path. At first glance, contradictions within and between these sources hamper the reliability of Einstein's accounts. Yet, a closer analysis reveals much more consistency than foreseen and helps eliminate the dubious, contradictory elements. It then becomes possible to combine the three kinds of sources to produce a minimally speculative and yet fairly coherent account of the genesis of special relativity.

*Keywords:* Einstein, special relativity, recollections, reconstruction

The conceptual changes brought by the theory of relativity are so important that we all want to know how they happened. There are unfortunately few sources from which we can try to reassemble the thoughts through which Albert Einstein arrived at the special theory. These sources are of three kinds. Firstly, a few letters document the young Einstein's interest in the optics and electrodynamics of moving bodies, which was the main context of emergence of the new theory (D sources). Secondly, after arriving at special relativity Einstein often included an impersonal account of its genesis (G sources). Thirdly, in a few occasions Einstein described

what he believed to have been his own path to the theory (H sources). For a long time, the largest portion of the D sources, which is Einstein's correspondence with Mileva Marić, was unavailable, and historians had to content themselves with G and H. The reliability of the latter sources is dubious, since there are contradictions among them and with the D sources. As Gerald Holton remarked long ago, the G sources belong to the context of justification and they need not represent the way in which Einstein truly arrived at the theory; most of the H sources are recollections reported and processed by other authors, and the rest of them came so late in Einstein's life that one may doubt the accuracy of his memory. The D sources are of course the most reliable, but they are too scarce to sustain a reasonably complete story.<sup>1</sup>

In face of this archeological dilemma, historians have hesitated between two different attitudes. The first is to focus on the D sources and to discuss the steps documented by these sources in a historically documented context, leaving the rest of the story undetermined. In the second attitude, one tries to fill the blanks in a speculative manner, and picks those of the G or H sources that best support the desired story. In my own writings on the history of special relativity, I have favored the first attitude and shunned reference to post-1905 sources, judging them altogether unreliable.<sup>2</sup>

Recently, I decided to read as many of the G and H accounts as I could find, mostly because I thought they would be interesting revelators of Einstein's conceptions at the time of speaking or writing. To my surprise, I found more coherence than contradiction between the G, H, and D sources. The various G accounts complement each other more than they contradict

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<sup>1</sup> Holton 1969, pp. 145–146, 183–184 (see also Stachel 1982). The correspondence with Marić became accessible in 1986.

<sup>2</sup> Some of the best examples of the second attitude are Holton 1960, 1969, 1973; Miller 1981; Pais 1982, Chap. 3; Stachel 1995; Rynasiewicz 2000; Galison 2003; Norton 2004, 2014; Martínez 2009, Chap. 6; Weinstein 2015. The purest example of the first attitude is Stachel et al. 1987, 1989.

each other. The few contractions of the G and H accounts and between the H accounts are either solved by referring to the D sources or attenuated by taking into account the context in which they were produced. Then I decided to combine all D, G, and H sources to construct the fullest narrative possible. The result is still uncertain, for consistency is not a sufficient criterion of truth. But it may have more probability than accounts that cherry-pick a few of Einstein's remarks and rationally extrapolate between them.

Section 1 of this paper briefly summarizes the mechanical, optical, and electrodynamic knowledge Einstein exploited on his way to special relativity. Section 2 briefly recalls the structure of the theory given in Einstein's seminal article of 1905. (These two first sections may be skipped by readers already familiar with the context and content of relativity theory.) Section 3 is devoted to the G accounts and to their mutual consistency. Section 4 discusses the fewer H accounts, their mutual consistency, and their compatibility with the G accounts. Section 5 deals with the D sources, their interpretation, and their compatibility with the G and H accounts. Section 6 offers a tentative synthesis of all these sources in a single narrative of Einstein's peregrination toward special relativity. Among the issues decided in this account are Einstein's early attitude toward the ether, the role of Fizeau's experiment of 1851, the role of the Michelson-Morley experiment, the role of the electromagnetic-induction argument with which Einstein started his article of 1905, the reasons and timing of his adoption of the relativity principle, the theoretical options he considered on the basis of this principle, and the origin of his final redefinition of time. The discussion does not include the inertia of energy, nor the principle of equivalence and the transition toward general relativity, for these two developments do not much depend on the precise way in which Einstein arrived at special relativity. In agreement

with the casual style of Einstein's own historical accounts, experimental and mathematical technicalities will be kept to a minimum.<sup>3</sup>

## 1. Some background

This preamble will not give a balanced picture of the optics and electrodynamics of moving bodies in the years preceding relativity theory. Its only purpose is to summarize the results that need to be known to understand Einstein's accounts of the origins of relativity theory, with concomitant bias toward the authors Einstein read or referred to.

Since Galileo, Huygens, and Newton, it was well known that mechanical phenomena in a closed system are not affected by a common uniform translation impressed on this system, despite Newton's referring the laws of mechanics to absolute space. This invariance was named *Principe des mouvements relatifs* in nineteenth-century French treatises (Einstein read one of them, by Jules Violle). In the second half of that century, there was a growing German trend to reject Newton's absolute space and to regard all inertial frames as strictly equivalent. Einstein was certainly aware of this trend, at least through his reading of Ernst Mach's *Mechanik* in the late 1890s. Before 1905 he could find the name *Principe de relativité* in Henri Poincaré's *La science and l'hypothèse*, for the impossibility to detect effects of a global uniform translation of the experimental setup not only in mechanics but also in optics and electrodynamics.<sup>4</sup>

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<sup>3</sup> The reader who is not already familiar with the technicalities may find them described in Miller 1981; Darrigol 2000, 2005, 2021; Weinstein 2015.

<sup>4</sup> Violle 1883, pp. 86–87; Mach 1883; Poincaré 1902, p. 281. On Einstein reading these texts, see *ECP* 2, pp. 258–259; *ECP* 1, p. 230; Solovine 1956, p. 8.

In Fresnel's optics, light was a transverse vibration propagated in a specific elastic medium, the ether. In order to explain stellar aberration, Augustin Fresnel (and Leonhard Euler before him) assumed the ether to be undisturbed by the motion of the earth through it, so that light would propagate rectilinearly from a star to the earth, with an aberration angle caused by the earth's displacement in the time needed for the stellar light to reach it. In order to explain François Arago's failure to observe an effect of the earth's motion on the refraction of starlight by a glass prism, Fresnel further assumed that when a transparent body moved at the velocity  $\mathbf{v}$  in the ether, the velocity of light in the body as judged from the ether frame was given by  $c/n + (1 - 1/n^2)v_x$  where  $v_x$  denotes the projection of  $\mathbf{v}$  on the direction of propagation,  $n$  the optical index of the body, and  $c$  the velocity of light in vacuum (see Appendix 1). Fresnel pictured this result as a partial drag of the ether by the body, with the dragging coefficient  $1 - 1/n^2$ . In 1851, Hippolyte Fizeau directly verified the Fresnel drag by measuring the phase shift of light traveling through running water in a clever interference device (see Fig. 1).<sup>5</sup>

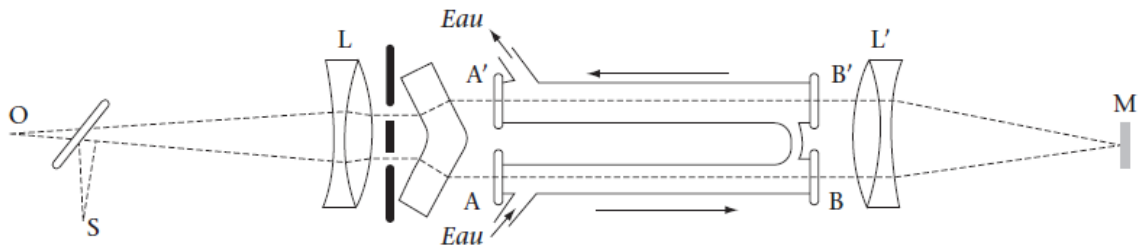


Fig. 1: Fizeau's ether-water experiment. One portion of the light from the source  $S$  travels along running water in the tube  $AB$ , and along the running water of the tube  $A'B'$  after reflection on the mirror  $M$ . The other portion travels twice against the running water. The two portions interfere in  $O$ , with a phase difference depending on the velocity of the water.

<sup>5</sup> Fresnel 1818; Fizeau 1851, 1859. On the history of the optics of moving bodies, see Mascart 1872, 1874; Whittaker 1951; Hirose 1976; Acloque 1981; Janssen and Stachel 2004; Stachel 2005; Eisenstaedt 2005; de Andrade Martins 2012.

As the earth moves through Fresnel's stationary ether during its rotation around the sun, one should generally expect effects of this motion on optical experiments on earth. Yet, all along the nineteenth century most attempts to detect this motion by refraction, interference, or diffraction failed. Arago's prism experiment was the first null result of this kind, and Fresnel's theory was the first example of a theoretical compensation of the expected effect by a well-adjusted ether-matter interplay. In the 1870s, there were general proofs that Fresnel's partial drag, the Doppler effect, and Huygens's principle together implied the absence of effects of the earth's motion to first order in the ratio  $u / c$  of the velocity  $u$  of the earth to the velocity of light (henceforth I will just write "to first order").<sup>6</sup>

In the 1860s, James Clerk Maxwell developed an electrodynamic theory in which electromagnetic processes were traced to four vector fields representing the state of a compound medium of ether and matter. In order to include the electrodynamics of moving bodies, for instance the induction of currents by moving magnets, Maxwell simply assumed the medium to follow the motion of matter. Under this assumption, the field equations in the presence of moving matter easily obtain from the equations in the case of complete rest by inserting convection terms in them. In 1890, Heinrich Hertz generalized this procedure to reach a complete, consistent electrodynamics of moving bodies in agreement with all known phenomena involving moving dielectrics, conductors, and magnets. Two years earlier, Hertz had proved the existence of electromagnetic waves. This discovery and his subsequent reformulation of Maxwell's theory were highly influential, especially in Germany. Whereas Maxwell and his disciples wanted a mechanical explanation of the electromagnetic states of the medium, Hertz

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<sup>6</sup> See Mascart 1872, 1874.

and his German followers abandoned this sort of reduction and simply posited the existence of the electromagnetic field as a *sui generis* state of the medium.<sup>7</sup>

One of Maxwell's great successes was the electromagnetic theory of light, in which a light wave is represented by transverse electric and magnetic fields in the (isotropic) medium. As Maxwell and his disciples realized, the simple assumption of a single, continuous ether-matter medium did not suffice to account for optical dispersion and it did not easily accommodate the phenomena of the optics of moving body. Maxwell's fully dragged ether is indeed incompatible with Fizeau's result, and some contortion is needed to reconcile it with stellar aberration. In 1890, Hertz admitted that in a successful optics of moving bodies, ether and matter would probably have to be separated from each other.<sup>8</sup>

The separation of ether and matter was already known to be necessary in optics to explain dispersion, crystal optics, and magneto-optic phenomena. It usually went along with a discrete representation of matter. In electrodynamics, Hermann Helmholtz defended the atomicity of electricity to explain electric conduction and polarization through the movement of ions, against the Maxwellian idea of charge and current as a process deriving from a macroscopic, irreducible concept of polarization. In 1893, he gave an electromagnetic theory of dispersion based on the interaction between ether in vacuum and vibrating ions. Unknown to him, a young Dutch theorist, Hendrik Lorentz, had already developed a similar theory with the higher ambition to cover all known optical and electrodynamic phenomena. In 1892, assuming the ether to remain immobile during the drift of matter and its ions through it, Lorentz had been able to derive Fresnel's drag formula. From a formal point of view, this theory is based on Maxwell's equations

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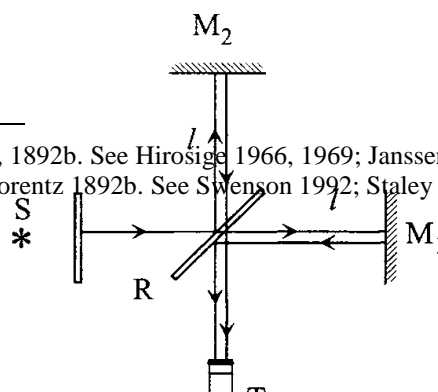
<sup>7</sup> Maxwell 1861–1862, 1865, 1873; Hertz 1890a, 1890b, 1892. See Buchwald 1985, 1994.

<sup>8</sup> Hertz 1890b, p. 285. On the need to separate ether from matter, see Buchwald 1994, Parts 3–4. In Britain, physicists doubted Fizeau's result and long supported George Stokes's theory of aberration, which relied on a fully dragged ether in irrotational motion (see Whittaker 1951, Chap. 12).



in vacuum in the ether frame, with source terms corresponding to the charge and convection current of ions (later electrons); and the so-called Lorentz-force formula for an ion or electron immersed in the electromagnetic field (see Appendix 2). Through a Galilean transformation Lorentz obtained the field equations in the earth frame. He realized that at first order these equations could be brought back to their original form (in the ether frame) by replacing the true time  $t$  with the "local time"  $t - \mathbf{u} \cdot \mathbf{r} / c^2$  ( $\mathbf{u}$  denotes the velocity of the earth and  $\mathbf{r}$  the position in the earth frame), with concomitant transformations of the electric and magnetic fields (see Appendix 2). This time shift being irrelevant to the stationary light intensity patterns on which all optical experiments were based, Lorentz concluded that his theory globally explained the lack of effects of the earth's motion on optical experiments.<sup>9</sup>

This "correspondence theorem" was limited to first order, and it was easy to see that the motion of the earth should have second-order effects. For instance, the time taken by light on a round trip between two locations A and B on earth should depend on the angle between AB and the velocity  $\mathbf{u}$  of the earth. In 1887, Albert Michelson and Edward Morley compared the round trips in two perpendicular directions by means of interference and found the expected fringe shift lacking (see Fig. 2). In 1892, Lorentz explained this null result through a contraction of the arm of his interferometer in the direction of the motion of the earth, by the amount  $\sqrt{1 - u^2 / c^2}$ . He justified this contraction by assuming that the electric and cohesive forces among the molecules of a rigid bodies were all affected in a similar manner by the motion of the earth through the ether.<sup>10</sup>



<sup>9</sup> Helmholtz 1893; Lorentz 1892a, 1892b. See Hirose 1966, 1969; Janssen 1995, 2019.

<sup>10</sup> Michelson and Morley 1887; Lorentz 1892b. See Swenson 1992; Staley 2008, Chap. 2.

Fig. 2: Michelson's interferometer and experiment. The light from the source S travels through two different paths determined by the semi-reflecting plate R and the mirrors M<sub>1</sub> and M<sub>2</sub>, and then recombines to form interference fringes seen through the telescope T. If the interferometer moves through a stationary ether, for instance in the direction SM<sub>1</sub> of the first arm, then the mirror M<sub>1</sub> moves forward at the velocity  $u$  during the light's travel from R to M<sub>1</sub> in the ether, and the needed time is  $l / (c - u)$ . The time needed for the return trip is  $l / (c + u)$ , and the round trip takes  $\tau_1 = (2l / c)(1 - u^2 / c^2)^{-1}$ . The time  $\tau_2$  needed for the round trip between R and M<sub>2</sub> is  $(2l / c)(1 - u^2 / c^2)^{-1/2}$  because the light path in the ether is twice the hypotenuse of a rectangular triangle of sides  $l$  and  $u\tau_2 / 2$ . The expected phase-shift is proportional to the difference  $\tau_1 - \tau_2$ .

Lorentz synthesized these results and much more in his influential *Versuch* of 1895. In 1899 and in 1904, he was able to generalize the absence of optical effects of the earth's motion at any order, using transformations that exactly brought back the field equations in the earth frame to the original equations in the ether frame (our "Lorentz transformations" are the product of such a transformation with a Galilean transformation), save for negligible discrepancies in the source terms (see Appendix 2). In Lorentz's eyes, the transformed fields and coordinates were purely formal, and the invariance of the field equations did not directly translate into the invariance of phenomena. Moreover, the formal invariance was not exact for the source terms.

This is why Lorentz continued to believe in the existence of effects of the earth's motion on electrodynamic experiments in general. At the turn of the nineteenth and twentieth centuries, the only scientist to defend the strict validity of the relativity principle was Henri Poincaré. All other theorists believed that motion through the ether should have physical effects, even though various compensation mechanisms pushed them beyond contemporary means of observation.<sup>11</sup>

## 2. Einstein's theory of 1905: An outline

The theory expounded in Einstein's famous article of 1905 "On the electrodynamics of moving bodies" may be summarized as follow.<sup>12</sup>

### *First section: Kinematics*

Einstein picks an inertial frame (in which the mechanical principle of inertia holds), calls it the "rest system" by mere convention, and defines the time  $t_A$  at the location A in this frame through the indication of a clock kept in A. In order to unify the indications of clocks situated at different locations, he assumes the possibility of optically synchronizing them according to the rule: if a light signal is sent from A at time  $t_A$ , is reflected by a mirror in B at time  $t_B$ , and returns to A at time  $t'_A$ , then the relation  $t_B - t_A = t'_A - t_B$  holds. Einstein further assumes that in the rest frame and for clocks thus synchronized, the velocity of light sent from A to B, namely, the ratio  $AB / (t_B - t_A)$  is the constant  $c$ , whether the source is moving or not. This is the *light principle*.

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<sup>11</sup> Lorentz 1895. On Poincaré's views, see Galison 2003; Katzir 2005.

<sup>12</sup> Einstein 1905.

In Lorentz's theory, these definitions and this principle would make obvious sense in the ether frame, in which the velocity of light is a uniform characteristic of the ether. Einstein departs from Lorentz by assuming the *relativity principle*, according to which the laws of evolution of the states of a physical system are the same in any inertial system (moving rectilinearly and uniformly with respect to the rest system). In this statement, Einstein includes not only the laws of mechanics but also the laws of optics and electromagnetism. Then the velocity of light must be the same constant  $c$  in any inertial system, and consequently, as Einstein shows through now classical reasoning, length, duration, and simultaneity become relative notions. Einstein next derives the transformation relating the space and time coordinates in the rest frame to the coordinates in another inertial frame moving at the constant velocity  $\mathbf{u}$  in the former frame. For a proper choice of axes, this transformation reads

$$t' = \gamma(t - ux / c^2), \quad x' = \gamma(x - ut), \quad y' = y, \quad z' = z, \quad \text{with } \gamma = (1 - u^2 / c^2)^{-1/2}.$$

It preserves the form  $c^2 t'^2 - x'^2 - y'^2 - z'^2$ , as ought to be for the velocity of light to be the same in both reference frames. Based on this transformation, Einstein derives the  $\gamma^{-1}$  contraction of a rod attached to the x-axis of the moving frame, and the  $\gamma$  dilation of the time of a clock attached to the moving frame, when the measurements are done in the rest frame. He also derives the relativistic law for the addition of velocities.

### *Second section: Electrodynamics*

Einstein proves the invariance of the Maxwell-Lorentz equations in vacuum under the former coordinate transformation and a concomitant field transformation (see Appendix 2). He uses these transformations to derive the (relativistic) Doppler effect, stellar aberration, the transformation rule for the energy of a "light complex," and the value of radiation pressure on a

moving mirror. He next derives the invariance of the full Maxwell-Lorentz equations, including the source terms. Lastly, he considers the motion of a particle of mass  $m$  and charge  $q$  in the electro-magnetic field  $(\mathbf{E}, \mathbf{B})$ . Assuming the validity of Newton's equation of motion  $m\ddot{\mathbf{r}} = q\mathbf{E}$  in a reference frame in which the velocity of the particle is a negligible fraction of  $c$ , and transforming to an arbitrary frame, he derives a relativistic equation of motion that we would now rewrite as  $\mathbf{f} = d\mathbf{p} / dt$ , with  $\mathbf{f} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$  for the Lorentz force, and  $\mathbf{p} = m\gamma\dot{\mathbf{r}}$  for the relativistic momentum.

### *Einstein versus Lorentz*

There are obvious differences between this theory and Lorentz's. Whereas Lorentz preserved Newton's absolute time and treats his local time as an uninterpreted, auxiliary variable, Einstein makes time depend on the reference frame and regards the local time as the time measured by moving observers. More generally, the Lorentz-transformed fields and coordinates, which Lorentz associates with "corresponding states" of a fictitious system, become the fields and coordinates measured by moving observers for Einstein. Whereas for Lorentz there is a privileged frame, the ether frame, in which the Maxwell-Lorentz equations hold, for Einstein all inertial frames are strictly equivalent and the ether can be dispensed with. Einstein's relativity principle requires the *laws* of physics to have *exactly* the same form in any inertial frame, whereas Lorentz's theory requires only the *approximate* invariance of the *phenomena* observed in moving (inertial) frames. Whereas Lorentz arrives at the coordinate transformations by formal compensation of the effect of a Galilean transformation on the field equations, Einstein obtains these transformations by requiring the constancy of the velocity of light in both of the compared frames. Whereas Lorentz derives the motion of an electron in an electromagnetic field from a

specific model of the electron, Einstein obtains it by relativistic covariance combined with a correspondence principle.

These conceptual differences are so important that one naturally wonders how they could arise. We will now look at the clues given by Einstein himself.

### 3. Einstein's genetic accounts

This label includes remarks Einstein made in his expositions of special relativity regarding the circumstances that lead or led to this theory, without specifying the extent to which these circumstances determined his own path. The first remarks of this kind belong to the seminal article of 1905; the last I will consider are found in the popular book Einstein and Leopold Infeld published in 1938.

G1: *On the electrodynamics of moving bodies* (Einstein 1905)

- In electrodynamics, the current induced in a coil by a magnet depends on the relative velocity of the coil and magnet. Yet, in Lorentz's electrodynamics of moving bodies, a different cause is given to the induced current depending on whether it is the coil or the magnet that moves with respect to the ether. In the first case, there is no electric field in the coil and the current is caused by the Lorentz force  $e(\mathbf{v} \times \mathbf{B})$  acting on the coil's electrons ( $e$  for their charge,  $\mathbf{v}$  for their velocity); in the second case, an electric field  $-e\partial\mathbf{A} / \partial t$  acts on these electrons (with  $\mathbf{B} = \nabla \times \mathbf{A}$ ). In a good theory, there should not be such asymmetry without phenomenal counterpart.
- In addition, all attempts to detect effects of motion of the earth through the ether have failed (Einstein does not mention specific attempts).

- In mechanics there is no absolute rest and all inertial frames are strictly equivalent.
- In Lorentz's theory, despite the assumption of an immobile ether, there is no first-order effect of the motion of the earth through the ether.
- These considerations together lead to the *relativity principle* according to which the same laws hold in any inertial frame for mechanical, optical, and electrodynamic phenomena.
- As a second principle, Einstein assumes that in a vacuum the velocity of light is a constant that does not depend on the motion of the source—as is the case in the ether frame in Lorentz's theory.
- The seeming contradiction between these two principles is solved by attending to the operations through which space, time, and motion are concretely defined. A new kinematics is born.
- These redefinitions lead to the Lorentz transformations for space and times coordinates.
- The Maxwell-Lorentz equations turn out to be invariant through these transformations.
- The ether becomes superfluous.

G2: *On the relativity principle and the conclusions drawn from it* (Einstein 1907)

This is the review article Einstein wrote at Johannes Stark's request for the *Jahrbuch der Radioaktivität und Elektronik*. The genetic points are as follows.

- The laws of mechanics are Galilean-invariant.
- Lorentz's immobile ether formally contradicts this invariance.
- Yet there is no first-order effect of the motion of the earth through the ether in Lorentz's theory.
- The Michelson-Morley experiment disproves a second-order effect of this motion.

- The Lorentz-FitzGerald explanation of this null result thought the Lorentz contraction is artificial, because in a good theory the lack of effects of the earth's motion should be directly derivable from a symmetry of the theory.
- Surprisingly, these difficulties can be solved by sharpening our concept of time. The key is to realize that Lorentz's local time (through which the Maxwell-Lorentz equations in a moving frame retrieve the same form as in the ether frame, to first order) can be defined as the time *tout court*.
- The Maxwell-Lorentz equations are invariant through the transformations corresponding to this new concept of time. Lorentz's theory is thus reconciled with the relativity principle.
- The fields become self-contained entities, and no ether is needed.
- What makes the reinterpretation of the local time possible is a new kinematics based on rigid rods and generic clocks.
- The synchronization of clocks should be based on the principle of the constant velocity of light, which is a consequence of the corroborated content of Lorentz's theory.

There are significant differences between these two first geneses. The electromagnetic-induction argument no longer occurs in G2. Instead the Michelson-Morley experiment and the artificial character of the Lorentz contraction are brought to the fore. Whereas in G1 there is no mention of Lorentz's local time, in G2 Einstein makes it the formal trigger of his redefinition of time. From G1 we get the feeling that firstly the conflict between the two principles led to his redefinition time through optical synchronization, and secondly this redefinition yielded the Lorentz transformations from this redefinition. In the G2 picture, Einstein first realized that Lorentz's first-order local time called for optical synchronization, and then used the operational



synchronization to derive the exact Lorentz transformations; the new kinematics came as an afterthought of the local-time revelation.

G3: *On the development of our views concerning the nature and constitution of radiation*  
(Einstein 1909)

This is Einstein's address of 21 September 1909 at the *Naturforscherversammlung* in Salzburg.

The following points are made.

- In the aftermath of Maxwell's electromagnetic theory of light, physicists gradually ceased to seek mechanical representations of the states of the light medium. The ether no longer had internal motions, but it could still have bulk motion. An important question was whether the ether partook in the motion of matter.
- Fizeau's experiment of 1851 showed that the ether did not follow the motion of matter.
- Then, under the atomist assumption according to which matter is mostly made of void, the ether should be completely immobile, the earth should move freely through it, and there should be observable effects of the resulting ether wind.
- Experimentalists repeatedly failed to detect such effects.
- Lorentz's theory, despite its privileged ether frame, could explain these null results at first order, and it could also account for Fizeau's result.
- Then came the Michelson-Morley experiment, which contradicted a second-order effect of the ether wind.
- The Lorentz-FitzGerald explanation of this null result was artificial.
- Michelson's null result suggested the relativity principle, according to which the laws of physics should be the same in any inertial frame.

- Taking this principle at face value, one should renounce the ether, since Lorentz's stationary ether defines a privileged frame.
- Radiation thus becomes a self-contained entity, in analogy with the light corpuscles of the old emission theory of light.
- The relativity principle still seems to contradict Lorentz's theory, because in this theory there is a reference frame in which the velocity of light is a constant, which seems to imply that this velocity is no longer a constant in moving frames.
- This contradiction is solved by attending to the concrete definition of space and time coordinates through rigid rods and generic clocks.

The chief novelty of G3 is the introduction of the Fizeau experiment to justify the stationary ether. Indeed G3 goes further back in time than G1 and G2, which both presuppose Lorentz's theory as an established, successful electrodynamics of moving bodies. Like G1, G3 brings forth the conflict between the relativity principle and the light principle. Unlike G1, G3 does not refer to electromagnetic induction, but it broadly denounces the unobservable asymmetry introduced by the ether frame in Lorentz's theory. More like G2, G3 gives an important role to the Michelson-Morley experiment in suggesting the relativity principle.

G4: *The principle of relativity and its consequences in modern physics* (Einstein 1910)

The story in this text, written for the *Archives des sciences physiques et naturelles* in Geneva, is essentially the same as G3, except that Einstein now details how Lorentz's *Versuch* of 1895 exploited the stationary ether as the simplest assumption compatible with the atomistic concept of electricity and with the Fizeau experiment. Also, Einstein now gives a detailed account of the Michelson-Morley experiment. Again he denounces the artificial character of the FitzGerald-

Lorentz explanation. He introduces the relativity principle as a generalization of the Galilean principle of mechanics, generalization suggested by the Michelson-Morley experiment.

At this point, Einstein cites electromagnetic induction as a simpler case of theoretical asymmetry without phenomenal counterpart, adding that there would be many other examples of the same kind. He fully explains how relativity theory solves this difficulty, by making the electric-magnetic divide a function of the reference frame. The electric and magnetic fields are no longer states of the ether; they are defined in relation to a reference frame. Einstein goes on with the seeming contradiction between the relativity principle and the light principle, and then redefines time to solve this contradiction. A footnote deflects a naïve operationalist reading of the new kinematics: one could well define coordinates in a purely mathematical manner, and then eliminate the coordinates to form observable quantities.<sup>13</sup>

G5: *The theory of relativity* (Einstein 1911)

The argumentation of this address for the Zürich scientists is about the same as in G3 and G4, although it is expressed more concretely with laboratories and trains.

G6: *Manuscript on the special theory of relativity* (Einstein [1912–14])

This manuscript is an unpublished review article that Einstein wrote for Erich Marx's *Handbuch der Radiologie* between 1912 and 1914.

- It begins with a detailed exposition of Lorentz's theory, including the average macroscopic equations in dielectrics in motion, written in the ether frame. The plane-wave solutions of these

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<sup>13</sup> Einstein 1910, pp. 142, 25n–26n.

equations lead to the Fresnel-Fizeau drag. Einstein then turns to special relativity, walking the reader through the following points:

- Lorentz's theory implies the constancy of the velocity of light in vacuum in the ether frame, hence the light principle according to which there exists a reference frame in which the velocity of light in vacuum is a constant.
- The laws of classical mechanics are invariant under Galilean transformations. Consequently, their expression is the same in any inertial frame.
- This relativity extends to electrodynamic phenomena, as suggested by the failure to detect effects of the motion of the earth by optical means, especially by the "fundamentally important" Michelson-Morley experiment.
- There is a conflict between the relativity principle and the light principle, as long as we stick to the usual rule for the composition of velocities.
- A first way out of this difficulty would be to give up the constancy of the velocity of light.
- Fizeau's result, combined with the usual composition of velocities, gives  $c/n - v/n^2$  for the relative velocity of light in a transparent medium of index  $n$  moving at the velocity  $v$  with respect to the earth and source. There are two possible causes for this variation of the relative propagation velocity: the motion of the earth with respect to the medium, or the motion of the source with respect to the medium. The first option sounds too complicated. The second, adopted by Walther Ritz in 1908, implies that a plane wave would no longer be characterized by intensity, frequency, and polarization only but would also depend of the velocity of the source. It seems impossible to find a wave equation compatible with this state of affairs. Moreover, as

Einstein adds after becoming aware of Willem de Sitter's relevant observations in 1913, the emission theory would imply an unseen distortion of the apparent orbit of double stars.<sup>14</sup>

- The true way out of the conflict between the relativity principle and the light principle is to replace the Galilean transformations with the Lorentz transformations.
- This replacement is justified by an analysis of space and time measurement through rigid rods and generic clocks optically synchronized.
- As Laue first remarked in 1906, the aforementioned difficulty with Fizeau's result disappears when the usual addition of velocities is replaced by the relativistic rule that derives from the Lorentz transformations.<sup>15</sup>

The essential novelty of G6 is the consideration of the emission theory as a way to make electrodynamics and optics compatible with the relativity principle. Fizeau's result of 1851 now matters in three different ways: as a cardinal prediction of Lorentz's theory, as a stumbling block for the emission theory, and as a vindication of the relativistic rule for the composition of velocities.

#### *G7: The theory of relativity* (Einstein 1915)

In this semi-popular account written in 1913 and published two years later in Paul Hinneberg's *Kultur der Gegenwart*, the arguments are about the same as in G3, G4, G5, with the now familiar sequence: optical ether, Fizeau's experiment, Lorentz's theory, Michelson-Morley experiment, Galilean relativity in mechanics, relativity principle, light principle, conflict between these two principles, resolution by the new kinematics. The role of the Michelson-Morley experiment is emphasized:

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<sup>14</sup> Ritz 1908a, 1908b; de Sitter 1913.

<sup>15</sup> Laue 1907.

The successes of Lorentz's theory were so significant that the physicists would not have hesitated to give up the relativity principle if they had not been exposed to an important experimental result . . . , namely, Michelson's experiment.

There is no mention of the emission theory, only the remark that anyone who tried to solve the difficulties by replacing Lorentz's theory with another theory, had to renounce.<sup>16</sup>

G8: *Relativity lecture notes* (Einstein [1914–1915])

These lectures were given at Berlin University in the winter semester 1914–15. For the first time Einstein here refers to stellar aberration as a motivation for the stationary ether, although he still privileges Fizeau's experiment. He briefly mentions Ritz's emission theory and its refutation by de Sitter.

G9: *What is relativity theory?* (Einstein [1919])

In this text written for the London *Times* after the solar eclipse expeditions confirming the relativistic bending of starlight by the sun, Einstein introduces the theory of relativity as a "principle theory" (*Prinzip-Theorie*), according to the distinction he had earlier introduced between theories based on general architectonic principles and "constructive theories" based on a detailed model of the ultimate reality. The two principles of course are the relativity principle, here presented as a natural generalization of Galilean relativity in mechanics, and the light principle seen as a consequence of the Maxwell-Lorentz theory. Again, special relativity is introduced as a kinematic solution to the conflict between these two principles. Much of Einstein's text concerns the generalized relativity principle, the equivalence principle, and the resulting theory of gravitation.<sup>17</sup>

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<sup>16</sup> Einstein 1913, pp. 706 (citation), 707–708.

<sup>17</sup> On Einstein's distinction between principle-based theories and constructive theories, see Giovanelli 2020.

G10: *Fundamental ideas and methods of relativity theory* (Einstein [1920])

In this manuscript written for *Nature* though unpublished, Einstein introduces special relativity as "a contradiction-free fusion of the results of the Maxwell-Lorentz theory with those of classical mechanics." His outline of the genesis of this theory is similar to G3, G4, G5, G7. He notes, as in G3, that in late nineteenth-century electrodynamics, attempts to explain mechanically the electromagnetic states of the ether became growingly suspicious. In this occasion he refers to Poincaré's argument, in *La science et l'hypothèse*, that if you can find a mechanical model of the ether, then there necessarily exists an infinity of such models. The only mechanical property left to Lorentz's ether is its immobility!<sup>18</sup>

For justifying the relativity principle, Einstein again appeals to the Michelson-Morley experiment. Yet, at the beginning of the section on general relativity, he remarks:

In establishing the special theory of relativity, the following argument about Faraday's electromagnetic induction played a leading role [*eine führende Rolle*] . . . The phenomenon of electromagnetic induction forced me to postulate the (special) principle of relativity.

In this argument, the electric and magnetic fields appear to depend on the reference system.

Einstein goes on to assert that the gravitational field too is a frame-dependent concept if accelerated frames are considered in addition to the inertial frames of special relativity.<sup>19</sup>

G11: *Ether and the theory of relativity* (Einstein 1920)

In this Leiden lecture, Einstein's two main purposes are to bring out Lorentz's contribution to the electrodynamics of moving bodies and to show that the ether may in some sense be revived in

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<sup>18</sup> Einstein [1920], p. 245; Poincaré 1902, p. 197.

<sup>19</sup> Einstein [1920], pp. 264–265.

general relativity. Again, we read that Fizeau's experiment played an essential role in showing, along with stellar aberration, that the ether did not partake in the motion of matter.

Newer is Einstein's emphasis on Hertz's role in treating the internal states of the ether as *sui generis* states without mechanical underpinning. Also new is the remark that Hertz's theory, with its electromagnetic states in a moving medium, harbors an embarrassing duality: the medium has both non-mechanical states and a mechanical attribute of velocity. In addition, the complete ether drag assumed by Hertz is incompatible with Fizeau's result.

Einstein next explains how Lorentz vastly simplified the theory by assuming a strictly stationary ether in which atoms, ions, and electrons freely circulate. He repeats his witty remark (G20) that the only mechanical attribute left to Lorentz's ether is immobility. Special relativity removes this last attribute. The rest of Einstein's talk is more critical than historical and concerns the possibility of an ether concept in the now established theories of relativity. He prefers avoiding the Lorentz ether in special relativity for it would imply an asymmetry without phenomenal counterpart, while he recommends another kind of ether in general relativity as the intrinsic metric structure that mediates between the distribution of masses and the motion of masses.

#### G12: *Brief outline of the development of the theory of relativity* (Einstein 1921a)

In this article for *Nature*, Einstein begins with the usual sequence: Maxwell's electromagnetic theory, Hertz's fully dragged ether, Fizeau's contradiction, Lorentz's theory, Michelson-Morley, and the relativity principle. At this point, he brings forth the lack of invariance of Maxwell's vacuum field equations with respect to Galilean transformations. The cure is to replace these transformations with the Lorentz transformations based on a new practical kinematics. This



presentation brings forward the transformation properties of Maxwell's equations instead of the conflict between the relativity principle and the light principle. It agrees with Einstein's remark, in G2, that special relativity emerged from the remark that Lorentz's local time can be regarded as the true (relative) time.

### G13: *The evolution of physics* (Einstein and Infeld 1938)

In this popular book, Einstein and his collaborator Leopold Infeld begin the relativity story with the mechanical principle of relativity and go on with the optical and electrodynamic ether and the gradual demise of its mechanical attributes. They wonder about the propagation of light in a moving room when the source is at rest in the room. If the ether is co-moving (the room may just be a moving system of axes attached to the source), then the velocity of light judged from the rest frame should depend on the velocity of the source (according to the addition of velocities). This dependence failed to be seen on double stars, or in (Oliver Lodge's) ether-whirling experiments. Moreover, it has paradoxical consequences for an observer moving away from the source at a velocity higher than  $c$ . We are left with the stationary ether and anisotropic propagation on earth, in contradiction with Michelson-Morley. The rest of the story is as in the earlier G accounts.

### *Other geneses*

I have omitted a few very short and sketchy accounts, for instance the *Scientia* and *Vossische Zeitung* articles of 1914 and the London King's college lecture of 13 June 1921, also the account in Einstein's popular relativity book of 1917, because regarding the genesis of special relativity these accounts boil down to the conflict between the relativity principle of mechanics and the

light principle derived from Lorentz's electromagnetic theory, with occasional mention of de Sitter's refutation of propagation depending on the velocity of the source. In the King's college lecture, Einstein declares with splendid modesty that relativity theory is just "a natural development of a line that can be traced through centuries."<sup>20</sup>

Accounts written after 1920 bring little that is not found in earlier accounts, save for the Einstein-Infeld discussion of light propagation in a moving frame. In the Princeton lectures of May 1921, Einstein dwells on space measurement, with reference to Poincaré's kinesthetic analysis, in preparation to the new kinematics of special relativity; he presents the Maxwell-Lorentz theory and the constancy of the velocity of light as well confirmed by stellar aberration, Fizeau's experiment, and de Sitter's double-star observations. In a text of 1925 on non-Euclidean geometry in physics, he asserts that "without [Helmholtz on space measurement based on rigid bodies] the setting up of relativity theory would have been practically impossible" and he again refers to Poincaré. In the Nobel lecture of 1923, he cleanly distinguishes physical relativity from univocal coordination, and he introduces special relativity as an adaptation of the foundations of physics to the Maxwell-Lorentz electrodynamics.<sup>21</sup>

### *Synthetic remarks*

Einstein's genetic accounts varied in the course of time regarding scope, the choice of arguments, and the relative weighing of arguments. New elements were gradually brought in, but there is no significant contradiction between the various accounts. Putting everything together we get the following story.

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<sup>20</sup> Einstein 1914a, 1914b, 1917, 1921b (p. 431).

<sup>21</sup> Einstein 1923a, 1923b, 1925 (pp. 18, 19).

Wave optics and Maxwell's electromagnetic theory led physicists to assume the existence of a medium, the ether, whose internal states represent electromagnetic fields and light. In the late nineteenth century, Hertz and most physicists renounced the old quest for a mechanical explanation of these states, although they still admitted the possibility of a bulk motion of the ether around or in moving bodies. This raised the question of the amount of ether motion in the presence of moving matter. Assuming that the ether accompanies matter in its motion, as Hertz did in his electrodynamics of moving bodies, the velocity of light in a transparent body of index  $n$  moving at the velocity  $v$  in the laboratory should be  $c / n + v$  when measured in the laboratory in the direction of motion of the transparent body. Fizeau's experiment of 1851 instead gives  $c / n + \alpha v$  with  $\alpha \approx 0.4$ . This result cannot be explained by a partial drag of the ether in the proportion  $\alpha$  because, owing to optical dispersion, different light-frequencies would require different dragging velocities. The simplest is to assume a strictly stationary ether in which electric particles move freely and to explain Fizeau's result as a consequence of the interaction between the ether waves and the electric particles bound to the moving transparent body. This is what Lorentz did.

The laws of Newton's mechanics are the same in any inertial frame. This is the relativity principle of mechanics. In Lorentz's theory, there is a privileged frame bound to the immobile ether. Since the earth necessarily moves through this ether, we should expect optical and electromagnetic phenomena on earth to depend on the orientation of the experimental setup with respect to the velocity of the earth. However, Lorentz's theory implies the lack of first-order effects of this kind, in conformity with the null-result of most ether-drift experiments of the nineteenth century. Second-order effects are still expected, because the relative velocity of light on the moving earth depends on the direction of propagation (in a manner affecting the duration

of roundtrips at second order). In 1887 Michelson and Morley found this anisotropy lacking. Lorentz's explanation of this and other null results is artificial because it introduces a theoretical asymmetry without experimental counterpart: there is no observable difference between an optical or electrodynamic experiment performed in two different inertial frames, whereas the analysis of this experiment in a moving frame very much differs from the analysis in the ether frame. We should rather extend the relativity principle to optics and electrodynamics, and require the laws of physics to take the same form in all inertial frames.

Irrespective of the null result of ether-drift experiments, there is another reason to adopt the relativity principle. Even for simple electrodynamic phenomena, Lorentz's theory of the stationary ether implies asymmetries without empirical counterpart: electromagnetic induction receives a different explanation according as the coil or the magnet moves in the ether, even though the induced current is known to depend only on the relative motion of the coil and magnet.

In optics, one basic undesired asymmetry of Lorentz's theory comes from its requiring a constant velocity of light in the ether frame. Combined with the usual rule for the composition of velocities, this constancy implies anisotropic propagation in other inertial frames. A simple way to reconcile the optics and electrodynamics of moving bodies with the principle of relativity is to assume that the velocity of the source adds to the velocity of light, as it does in Newton's old emission theory. However, this option leads to absurd consequences when combined with Fizeau's result, and it seems incompatible with the existence of a wave equation for the field.

Then we should stick to Lorentz's assumption of the constancy of the velocity of light in the ether frame. But how could we reconcile this constancy with the relativity principle? From Lorentz, we know that Lorentz's equations are not invariant through a Galilean transformation:

new terms appear when the equations are written in a moving frame. However, (to first order) these new terms can be eliminated by introducing the "local time" instead of the true time. This local time turns out to be the time measured by optically synchronized clocks in the moving frame, assuming the velocity of light to be a constant in this frame. The key, Einstein tells us, is to attend to the operational grounding of our basic concept of time, as Helmholtz, Poincaré, and Mach recommended for other geometrical and mechanical concepts. Attention to the preconditions of measurement is here crucial. This new kinematics leads to the Lorentz transformations, under which the Maxwell-Lorentz equations turn out to be invariant. Lorentz's theory is thus fully reconciled with the relativity principle.

In the G accounts from which this story is built, Einstein does not give any timing for the successive arguments, and he rarely indicates whether or not he actually used them in his path toward special relativity. The one exception is the electromagnetic induction argument, which he occasionally claims to have been most decisive in his mind. Even if we had no independent documentation of Einstein's path, there are indirect means to weigh the historical relevance of the various arguments. Let us begin with his reliance on Fizeau's experiment. There are two reasons to believe that this experiment truly played an essential role in Einstein's thinking. The first is that it occurs in all of Einstein's accounts, except those that do not cover the pre-Lorentz period. The second, more compelling reason, is that no one except Einstein ever used Fizeau's result to justify the stationary ether.<sup>22</sup> The standard justification, for Lorentz and others, was agreement with Fresnel's theory of stellar aberration and simplicity. In contrast, Einstein started to cite stellar aberration only after 1914 and only as additional evidence for the stationary ether.

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<sup>22</sup> Poincaré used it to justify the separation of ether and matter.

The reference to the Michelson-Morley experiment as a motivation for the relativity principle is also omnipresent in Einstein's genetic accounts. The only exception is G1 of 1905, in which Michelson's null result may still be regarded as included in Einstein's generic reference to the null result of ether-drift experiments. As Holton remarked long ago, this convergence of the G accounts is not a sufficient reason to believe that the Michelson-Morley experiment truly played an essential role in Einstein's adoption of the relativity principle. It could be that after 1905 he decided that he would more efficiently promote special relativity by an empirical argument (the null-result of ether-drift experiments) than with an epistemological argument (univocal coordination). Indeed, in Einstein's successive accounts there is a trend to increase the list of supporting experiments. To justify the stationary ether and the constant velocity of light, he originally cited the Fizeau experiment only, later adding stellar aberration and de Sitter's observations on double stars.<sup>23</sup>

Still, judging from the G accounts only, it seems unlikely that the Michelson-Morley experiment played no role at all in Einstein's thinking. For it is hard to imagine that the electromagnetic-induction argument by itself drove him to adopt the relativity principle. The well-known relativity of the induction phenomenon could have been a first-order approximation only: in 1889 Theodor Des Coudres expected and tried to detect a second-order departure from this relativity. There were notable cases of phenomena whose relativity held only at first order, for instance the Doppler effect of acoustic waves: this effect depends on the relative motion of the source and receptor only to first order in the relative velocity, and no one would dream to modify acoustic theory to warrant exact relativity for the Doppler effect. Most likely, a confluence of arguments determined Einstein's adoption of the relativity principle: the null result

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<sup>23</sup> See Holton 1969; Stachel 1982.

of ether-drift experiments including Michelson-Morley's, the more epistemological argument regarding electromagnetic induction, and also the ether's gradual loss of all its mechanical attributes. Einstein's occasional insistence on the epistemological argument is easily explained by his awareness that the relativity of phenomena (a purely empirical fact) does not in itself entail the invariance of the theoretical representation.<sup>24</sup>

#### 4. Einstein's recollections

H1: *Einstein's Kyoto lecture (1922)*

On 14 December 1922, Einstein lectured at the physics department of Kyoto university on how he discovered the theory of relativity. The physicist Jun Ishiwara then published a Japanese version of the contents of this talk (the original, if it ever existed, is lost). Here are the main points regarding the origins of special relativity:<sup>25</sup>

- It all started with the optics of moving bodies. One usually assumed that the earth moved through the ether, and yet no one could find optical evidence for this motion.
- Einstein then "did not doubt at all the existence of the ether nor the motion of the earth" and imagined a new test of this motion, by comparing the intensities of the lights emitted from a terrestrial source in two opposite directions.<sup>26</sup>

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<sup>24</sup> Des Coudres 1889; Doppler 1842.

<sup>25</sup> Einstein [1922]. For the circumstances of this lecture, see Stachel 1982, pp. 47–48.

<sup>26</sup> with the comment (*ECP* 13, p. 636) : "This idea was the same as in Michelson's experiment, but my understanding of this experiment was not yet clear at the time."

- Einstein became aware of the Michelson-Morley experiment, gave up the ether wind, and adopted the principle of relativity.<sup>27</sup>
- Around the same time Einstein studied Lorentz's *Versuch* of 1895, which explained all known facts to first order.
- Ishiwara next reports Einstein to have said:<sup>28</sup>

I tried to account for [Fizeau's result] on the assumption that Lorentz's equations for the electron equally apply in the vacuum frame and in a frame attached to the moving body. At any rate, I believed at the time that the Maxwell-Lorentz equations were secure and represented the true state of affairs. The circumstance, moreover, that these equations also hold in a moving frame implies the invariance of the velocity of light. This invariance, however, is incompatible with the law of the additions of velocities known from mechanics.

- In face of this contradiction, Einstein vainly tried "to modify Lorentz's ideas" for about a year.
- The solution came to him in early 1905 after a conversation with Besso: time had to be redefined in a manner intimately related to the velocity of light signals. The theory of special relativity was then completed in five weeks.
- Einstein realized that this redefinition of time was in the spirit of Mach's critical attitude toward the basic concepts of mechanics.

For the most, this account is internally consistent, and it is compatible with the G accounts. Some points of these accounts are missing, for instance the role of Fizeau's experiment in Einstein's belief in the ether wind or the role of electromagnetic induction in his inclination

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<sup>27</sup> In the translation of *ECP* 13, p. 636, the relevant section reads: "I was familiar with the strange results of Michelson's experiment while I was still a student pondering these problems, and instinctively realized that, if we accepted his result as a fact, it would be wrong to think of the motion of the Earth with respect to the ether. This insight actually provided the first route that led me to what we now call the principle of special relativity." As noted in van Dongen 2009, this statement fits with another found in a lecture Einstein gave in 1921 in Chicago: "As a young man . . . I thought about whether it would be possible to perceive through some experiment that the earth moves in the ether. But when I was a student, I saw that experiments of this kind had already been made, in particular by your compatriot, Michelson. He proved that one does not at all notice on earth that earth moves, but that everything takes place on earth as if the earth is in a state of rest" (*ECP* 12, p. 519).

<sup>28</sup> *ECP* 13, p. 631. I thank Annik Horiuchi for checking details of the translation.



toward the relativity principle. Although there is no explicit mention of the emission-based attempt, Einstein evokes a year-long attempt to modify Lorentz's ideas. Most obscurely, he refers to an attempt to reconcile the Fizeau experiment with the relativity principle based on using the same field equations in the "vacuum" frame and in a moving frame (presumably bound to the running water). It is difficult to make sense of the cited extract of Ishiwara's notes: how could Einstein apply the Maxwell-Lorentz equations in two different (inertial) frames, knowing that they are not Galilean invariant?

Perhaps Einstein meant to attach the reference frame to the light source, as he did in the Einstein-Infeld argument of G13. Then there is no contradiction with the Galilean transformation, because the two compared fields concern two different physical situations expressed in the same rest frame: in the first situation, a source at rest sends light through a transparent body moving at the constant velocity  $v$  away from the source; in the second, the source is attached to the moving transparent body in which the light travels. In both situations, Einstein wants the Maxwell-Lorentz equations to be valid in the reference frame attached to the source. Then the velocity of light in the moving body as judged in the rest frame is  $c/n + (1 - 1/n^2)v$  in the first case (since the Maxwell-Lorentz equations then apply in the rest frame), and  $c/n + v$  in the second case since the velocity  $v$  of the body then adds to the velocity  $c/n$  of light given by the Maxwell-Lorentz equations in the moving frame. This means that the velocity of light  $V$  in a transparent body depends on the velocity  $u$  of the source with respect to this body. For a body of negligible optical density ( $n \approx 1$ ) and for propagation in the direction of the motion of the source, we simply have  $V = c + u$  as expected in an emission theory.<sup>29</sup>

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<sup>29</sup> Alfred Bucherer (1903, 1904, 1906, 1907) similarly assumed the principle of relativity and required the Maxwell-Lorentz equations to apply in any inertial system, without renouncing the Galilean transformations. As he made clear in 1906, he meant that these equations should be applied to a frame moving at the velocity of the particle on

To summarize, from G13 and also from G6, we gather that Einstein at some point combined Fizeau's result with the usual addition of velocities to arrive at propagation depending on the velocity of the source. The inference is direct in G6, whereas in G13 it is done through the Maxwell-Lorentz equations applied in two different frames attached to the light source. My guess is that the attempt mentioned in the Kyoto lecture is akin to G13. Without relying on Fizeau's result, Einstein could have simply reasoned that if the propagation of light from a moving source in vacuum is to be computed from Maxwell's equations in a frame attached to the source, then the velocity of light (in the rest frame) depends on the velocity of the source in the manner of emission theories. That he did not reason in this simpler manner may be explained by his desire to anchor his reasoning on a real experiment.

## H2: Wertheimer's reconstruction (1916–1943)

Max Wertheimer, a leader of gestalt-psychology and a friend of Einstein, long tried to reconstruct the train of thoughts that led Einstein to special relativity. The result appeared in 1945 as a chapter of his posthumous *Productive thinking*. He offered it as the result of hours and hours of conversation with Einstein, beginning in 1916. From the structure of the chapter and from extant correspondence with Einstein, it is clear that Wertheimer's chapter is a reconstruction based on some of Einstein's remarks, not the transcription of an account produced by Einstein himself. Wertheimer knew little physics and he wanted his book to be readable by laymen, so one should not expect much precision from him regarding physics concepts and reasoning.<sup>30</sup>

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which the Lorentz force acts. In my interpretation of Einstein's mysterious utterance, Einstein did the exact opposite: he assumed the Maxwell-Lorentz equations to hold in a frame moving at the velocity of the source of the field.

<sup>30</sup> Wertheimer 1945, Chap. 7. For a thorough study of this chapter, see Miller 1975.

Wertheimer distinguishes eight acts in the creative process that led Einstein's to special relativity (he has two more acts for general relativity). Here is the gist:

Act I: At age 16, Einstein imagined himself running after a light wave and thereby seeing a slower propagation and even no propagation at all when running at the speed of light. Moral: if light has a constant velocity in the ether, then this velocity should no longer be a constant for observers moving in the ether. Einstein planned experiments to test the resulting anisotropy when the earth moves through the ether, although "his wish to design such experiments was always accompanied by some doubts that the thing was really so."<sup>31</sup>

Act II: Einstein later reasoned as follows. In Newtonian mechanics, there is no absolute rest. In the ether-theory of light, one may define absolute rest as rest in the ether. But the ether is not a material thing; it is "the mere carrier of electrical phenomena." And attempts to detect the motion of the earth through the ether by optical means have so far failed. This suggests that the relativity principle of mechanics might extend to optics and electrodynamics.

Act III: In order to reconcile the relativity principle with Maxwell's electrodynamics, Einstein tried to modify Maxwell's equations so that they become invariant through Galilean transformations. Also, he considered the possibility that the velocity of light might depend on the velocity of the source. He failed to find field equations under these conditions.

Act IV: Michelson and Morley did not find the fringe shift implied by the motion of the earth through a stationary ether. This null result and earlier null results were "no surprise to [Einstein], although very important and decisive."<sup>32</sup>

Act V: Lorentz explained this result through the Lorentz contraction. But Einstein disliked this ad hoc move.

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<sup>31</sup> Wertheimer 1945, p. 169.

<sup>32</sup> Wertheimer 1945, p. 172.

Act VI: Einstein struggled to understand why the Michelson-Morley experiment did not detect different (relative) speeds of light in different directions.

Act VII: The key was that speed is defined through time measurement, which itself requires a definition of simultaneity. If we define distant simultaneity through light signals under the convention that the velocity of light is a constant, simultaneity and time become frame-dependent.

Act VIII: The constancy of the velocity of light in any inertial frame suffices to determine the space and time coordinate transformation from one frame to another. The laws of physics must be invariant under these transformations.

Act I is the first occurrence of the light-chasing thought experiment, which Einstein later mentioned in autobiographical writings. In the concise version of 1955 he wrote:

Running after a light wave at the velocity of light, one would face a time-independent wave field. Yet there seems to be no such thing! This was the first, childish thought experiment, that has to do with the special theory of relativity.

The fuller version for the Schilpp volume of 1949 reads:

If I pursue a beam of light with the velocity  $c$  (velocity of light in a vacuum), I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, neither on the basis of experience nor according to Maxwell's equations. From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. For how should the first observer know or be able to determine, that he is in a state of fast uniform motion? One sees that in this paradox the germ of the special relativity theory is already contained.

This statement has often been read as a suggestion that at age 16 Einstein already had an inkling of both the relativity principle and the invariance of the velocity of light. As we will see, the letters he wrote a couple of years later, in 1899, prove the contrary. For a nineteenth-century ether theorist, there was nothing absurd in the frozen oscillation seen by a wave-riding observer: Oliver Heaviside even wrote the equations for the arrested wave. Provided Einstein truly

imagined himself riding a light wave, he was not trying to abolish the ether. Wertheimer's account instead suggests that Einstein used this thought experiment to conceive the non-constancy of the relative velocity of light on earth. He did not reject this non-constancy; he believed it should be tested experimentally.<sup>33</sup>

Wertheimer nonetheless has Einstein "doubt" a positive result of the tests and thus be prepared to Michelson's null-result. He has Einstein try an emission theory (or a Galilean invariant modification of Maxwell's equations) before dwelling on the Michelson-Morley experiment. In this scenario, the experiment mattered not so much to Einstein's adoption of the relativity principle but as a concrete device of velocity comparison thought which Einstein came to rethink the definition of time. As Arthur Miller remarked, the order and relative importance of Wertheimer's Acts has to do with his desire to make the Michelson-Morley experiment the trigger of a decisive gestalt-switch. In a letter to Einstein, Wertheimer made clear that he originally started his reconstruction with the Michelson-Morley experiment and that he added the three first acts only after Einstein advised him to do so.<sup>34</sup>

There are evident similarities between the Tokyo lecture and the Einstein-Wertheimer account. In both, Einstein considered a stationary ether through which the earth is moving and he devised optical experiments to test effects of this motion. In both, the Michelson-Morley played an important role in Einstein's reflections. In both, it took Einstein a long time before he succeeded in reconciling the electrodynamics of moving bodies with the relativity principle; and in the meantime he considered options incompatible with Lorentz's theory. There are a few differences, however. Whereas Einstein-Ishiwara inferred the relativity principle from

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<sup>33</sup> Einstein 1955, p. 46; 1949, pp. 52–53; Heaviside 1888–89, Part 4. On the meaning of Einstein's thought-experiment, see Norton 2013.

<sup>34</sup> Miller 1975, pp. 91–92; Wertheimer to Einstein, 9 Aug. 1943, cited *ibid.* p. 89.

Michelson's null result, Einstein-Wertheimer was predisposed in favor of this principle well before he appreciated Michelson's result. Whereas Einstein-Ishiwara traces the decisive idea of a new kinematics to the conflict between the addition of velocities and the invariance of the velocity of light, Einstein-Wertheimer has it derive from a critical analysis of the Michelson-Morley experiment. Einstein-Wertheimer explicitly refers to the emission theory as an option investigated before special relativity, Einstein-Ishiwara is vaguer in this regard.

### H3: *Einstein's late recollections regarding the Michelson-Morley experiment (1942–1954)*

In the last years of his life, Einstein was repeatedly asked about the role of the Michelson-Morley experiment in his reflections toward relativity theory. In March 1942, in reply to the chemist-historian Bernard Jaffe, he wrote:

It is no doubt that Michelson's experiment was of considerable influence upon my work insofar as it strengthened my conviction concerning the validity of the principle of the special theory of relativity. On the other side I was pretty much convinced of the validity of the principle before I did know this experiment and its results. In any case, Michelson's experiment removed practically any doubt about the validity of the principle in optics, and showed that a profound change of the basic concepts of physics was inevitable.

This statement agrees well with Wertheimer's report, except for Wertheimer's contention that the Michelson-Morley experiment triggered Einstein's redefinition of time.<sup>35</sup>

In 1950, in an interview with the physicist Robert Shankland, who had a strong interest in the Michelson-Morley and derived experiments, Einstein said he had been aware of the experiment since he read Lorentz's *Versuch* but it "had come to his attention" only after 1905 since he did not mention it in his article of 1905. Presumably, he meant that he did not pay much attention to this experiment until, after 1905, he included it in accounts of the genesis of relativity theory. He added that the facts that truly mattered on his path to special relativity were

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<sup>35</sup> Einstein to Jaffe, 17 March 1942, cited in Holton 1969, p. 191.

stellar aberration and Fizeau's result. He also mentioned that he had considered and abandoned a variant of Ritz's emission theory before 1905. The main difficulties he encountered were the lack of a wave equation for this theory, and the absurd consequence that the light from an accelerated source could back up on itself. Two years later, Einstein told Shankland he did not exactly remember when he first became aware of the Michelson-Morley experiment, that he did not think this experiment directly influenced him in the seven years preceding the special theory, and that anyway he knew the result in advance.<sup>36</sup>

This 1952 assessment is duplicated in a machine-typed paragraph Einstein wrote late in the same year for Michelson's centenary:

I am not sure when I first heard of the Michelson experiment, or of its more precise repetition by Michelson and Morley. I was not conscious that it influenced me directly during the seven and more years that the development of the Special Theory of Relativity had been my entire life; for I had taken it for granted as being true.

However, Einstein crossed out this (English) text and wrote (in German):

[I addition to his experimental skills, Michelson] has shown an extraordinary understanding of the fundamental puzzles . . . This can be seen from the interest he had, from the beginning, in the dependence of light on motion.

My own thoughts were more indirectly influenced by the famous Michelson-Morley experiment. I learned about it through Lorentz's seminal investigation of the electrodynamics of moving body (1895), which I knew before devising the special theory of relativity. Lorentz's fundamental assumption of the immobile ether seemed unconvincing to me because it led to an interpretation of the Michelson-Morley experiment that seemed unnatural to me. My direct way to the special theory of relativity was principally determined by the conviction that the electromotive force in a conductor moving in a magnetic field is nothing different from an electric field. But the result of Fizeau's experiment and the phenomenon of aberration also guided me.

In the margin Einstein wrote:

There is no logical path to the formulation [*Aufstellung*] of a theory but only a groping fabrication [*tastendes Konstruieren*] with careful consideration of our factual knowledge.

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<sup>36</sup> Shankland 1963, pp. 47 (Michelson), 48 (Fizeau), 49 (emission), 55 (Michelson).

The main novelty is that Einstein now explains why he did not need the Michelson-Morley experiment: the magnetic-induction argument, together with Fizeau's null result and stellar aberration (already mentioned in the first interview with Shankland) were sufficient. This is quite different from the statement to Jaffe, which gave a non-negligible role to Michelson-Morley; and this agrees with Einstein's marginal remark that theories are free constructions of the mind, constrained but not logically implied by experimental facts. The suspicion runs high that Einstein was here inflecting his historical judgment to fit his late rationalism.<sup>37</sup>

A more detailed statement is found in the letter Einstein wrote to the historian Francis Garvin Davenport in February 1954. There he made the following points:<sup>38</sup>

- Before Michelson entered the scene, physicists had repeatedly failed to detect any effect of the motion of the earth on optical experiments. Lorentz's theory explained this failure to first order.
- However, this theory naturally included second-order effects of the ether wind.
- The Michelson-Morley experiment refuted an effect of this kind, and thus gave a new, strong argument for the inexistence of absolute motion not only in mechanics but also in optics and electrodynamics.
- Lastly:

In my own development Michelson's result has not had a considerable influence. I even do not remember if I knew of it at all when I wrote my first paper on the subject (1905). The explanation is that I was, for general reasons, firmly convinced that there does not exist absolute motion, and my problem was only how this could be reconciled with our knowledge of electro-dynamics. One can therefore understand why in my personal struggle Michelson's experiment played no role or at least no decisive role.

As Holton remarks, in this letter Einstein clearly distinguishes between his own indifference to Michelson's null result and the effect this result had (or should have had) on other

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<sup>37</sup> Einstein [1952]. On a possible rationalist distortion in Einstein's memories, see van Dongen 2009.

<sup>38</sup> Einstein to Davenport, 9 Feb. 1954, cited in Holton 1969, p. 194.



physicists' attitudes toward the relativity of motion. One can also observe that Einstein's memory is declining, since he no longer remembers whether he had known about the experiment before 1905 and since he significantly departs from his earlier statements. As John Norton puts it, the reader is left to imagine a "mystical prescience" of the young Einstein.<sup>39</sup>

#### H4: *Letters about the attempted emission theory*

As we just saw, H2 and H3 have mentions of Einstein's attempt to satisfy the relativity principle in an emission theory in which the velocity of propagation of electromagnetic waves depends on the velocity of the source. The earliest known reference to this attempt is found in Einstein's correspondence with Ehrenfest: in a letter of April 1912, Einstein refers to "Ritz's conception, which by the way was also mine before relativity theory." Einstein then deplores the impossibility of finding field equations that would make the propagation of light depend on the velocity of the source. Another class of objection concerns secondary, reemitted radiation when an incoming electromagnetic wave forces the electrons attached to a moving body to vibrate. In order to preserve the predictions of Lorentz's theory, one must artificially assume that the centers of secondary waves are at rest with respect to the primary source of light. This concerns moving screens, mirrors, and transparent plates. As Einstein explained to Ehrenfest, "for the explanation of shadow formation, one must introduce the ugly assumption that light emitted by a resonator depends on the type of excitation (excitation by moving radiation or excitation of another type)." In the same vein, in G6 Einstein noted that in order to retrieve the interference properties of light reflected by a mirror moving at the velocity  $v$  with respect to the source (in the normal direction), one had to assume the values  $c + v$  and  $c - v$  for the velocities of light with respect

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<sup>39</sup> Holton 1969, p. 194; Norton 2004, p. 45.

to the mirror before and after reflection. The more natural assumption that the center of secondary waves moves at the velocity of the secondary source leads to the implausible result that a thin moving glass plate would cause a shift of the interference fringes when placed before one of the slits of a double-slit experiment.<sup>40</sup>

Still another kind of objection, already encountered in H3, is detailed in a letter to Hines of 1952:

If an appropriately accelerated light source emits light in one direction (*e.g.*, in the direction of acceleration), then planes of equal phase move with different velocities, and thus one can arrange it so that all the surfaces of equal phase come together at a given location, so that the wavelength there becomes infinitely small. From there on the light reverses itself, so that the rear part overtakes the front.

In the same letter, Einstein deplored the absurdity of another consequence of the variable velocity of light:

If there is no fixed light velocity at all, then why should it be so, that all light that is emitted by 'stationary' bodies has a velocity *completely independent of the color*? This seemed absurd to me. Therefore, I rejected this possibility as a priori improbable.

All these objections were based either on thought-experiments or on the lack of a wave equation for the theory. Objections based on experimental facts, mainly de Sitter's failure to observe the distortion that the emission theory would imply for the orbits of double stars, need not concern us since they were not available to Einstein before 1905.<sup>41</sup>

### *Synthetic remarks*

There is a general trend in the evolution of Einstein's assertions regarding the role of the Michelson-Morley experiment in his own reflections, from the Kyoto lecture to the letter to

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<sup>40</sup> Einstein to Ehrenfest, 25 April 1912, *ECP* 5, p. 450; 20 June 1912, *ECP* 5, p. 485; Einstein [1912–1914], pp. 34–35. See Martínez 2004, pp. 9–11; Norton 2004 pp. 57–66, with the remark that Einstein's emission theory significantly differed from Ritz by preserving the wave picture.

<sup>41</sup> Einstein to Hines, Feb. 1952, Einstein Archive, cited in Martínez 2004, p. 10. See also Shankland 1963, p. 49.

Davenport: he gradually moved from an empiricist account in which the experiment determined his adoption of the relativity principle, to a rationalist view in which an inner conviction (of unspecified origin) of the truth of this principle preceded his attention to this experiment. For this reason and because the accuracy of recollections tends to decrease in time, we should be suspicious of Einstein's late statements that the Michelson-Morley experiment played nearly no role in his thinking. At the same time, the Kyoto statement that this experiment made him renounce the ether wind need not be equated with the stronger statement that this experiment was his sole reason for adopting the relativity principle. The Kyoto lecture is sketchy, lacunar, and suffers from ambiguities in the Japanese.<sup>42</sup>

If we compare the G and H accounts, we observe quite a few similarities. Firstly, nearly all these accounts have Einstein begin with a stationary ether and attempt to optically detect the motion of the earth through this ether. With regard to Einstein's adoption of the relativity principle, H1 confirms the contention of most G accounts that the Michelson-Morley experiment played an important role in this regard. Holton's suggestion that in the G accounts Einstein was not referring to his own path and was using this experiment only to justify the relativity principle does not work in the case of the Kyoto lecture, since Einstein was there telling the story of his own thoughts.

As for the electromagnetic-induction argument, it rarely occurs in the G accounts, and only in one in the H accounts (the 1952 manuscript for the Michelson celebration). Yet there is no reason to doubt Einstein's sincerity when in G10, two years before the Kyoto lecture, he claims that this argument played an essential role, no matter how important the Michelson-Morley experiment may also have been. Also, there is an indirect reason why this argument, and

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<sup>42</sup> See van Dongen 2009.

more broadly Einstein's intolerance of theoretical asymmetries that do not have any phenomenal counterpart, played a role in Einstein's path toward special relativity: without this argument he would have had no reason to eliminate the ether, he could have adopted Poincaré's and Lorentz's distinction between a true time in the ether frame and a merely apparent time in a moving frame.<sup>43</sup>

A notable difference between the G and H accounts concerns the role of Fizeau's experiment of 1851. This experiment plays a central role in all G accounts; it does not occur in H2; it occurs in H1, not as a justification of the stationary ether as in most G accounts but as a constraint on an alternative relativity theory (possibly an emission theory). These differences are explained by Wertheimer's intention to avoid technicalities in H2 and by noting that in H1 Einstein does not discuss the origin and motivation of the stationary ether.

As for what Einstein did after adopting the relativity principle, the attempted emission theory and the reasons of its failure are mentioned in both kinds of account (G6, G8, H2, H3, H4). For the final redefinition of time and space relations in a new kinematics, H1 and most of the Gs agree that light came to Einstein while brooding over the contradiction between the relativity principle and the light principle or, in the Kyoto version, over the contradiction between the invariance of the velocity of light and the addition of velocities. Only H2 tells a different story, making the Michelson-Morley experiment the trigger of Einstein's discovery of the relativity of synchronicity. As Miller argued, this exception is a probable artefact of Wertheimer's desire to fit Einstein's flash of insight in his gestalt-switch theory.<sup>44</sup>

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<sup>43</sup> On the epistemological significance of the argument, see Paty 1991, pp. 54–56. On its historical significance, see Norton 2004.

<sup>44</sup> Miller 1975, pp. 80–81, 91.

There is no trace, in the H accounts, of the G2 rendering of the decisive insight as the sudden awareness that Lorentz's local time could and should be regarded as the time *tout court*. However, H1 has Einstein apply the Maxwell-Lorentz equations in all inertial frames. As Einstein knew from Lorentz's *Versuch*, this is formally possible (at first order) by combining the Galilean transformation of spatial coordinates with a local time shift and an adequate transformation of the electric and magnetic fields. He may then have wondered whether the transformed time and fields were not the ones measured in the moving frame. Although there is no need to assume that Einstein truly proceeded by reinterpretation of Lorentz's local time as indicated in G2, this assumption makes it easier to understand how he dared to question absolute simultaneity.

## 5. Documents

There are no manuscripts documenting Einstein's pathway to special relativity. All we have are a few letters, conveniently gathered in the first volume of Einstein's *Collected papers*, which also includes an excellent introduction and discussion of all materials concerning the electrodynamics of moving bodies.<sup>45</sup>

D1: *The basic picture* (summer 1899)

From Einstein's correspondence, we gather that during his first three years at the ETH, in 1896–99, he read electrodynamics from three authors, Paul Drude, Helmholtz, and Hertz, who all

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<sup>45</sup> Stachel et al. 1987.

shunned any mechanical model of the ether. Drude avoided the concept of ether motion and regarded the ether as space endowed with special properties; Helmholtz pleaded for an atomistic conception of electro-optics in which electric particles moved freely through the ether; Hertz designed a purely macroscopic electrodynamics of moving bodies in which ether and matter moved jointly, although he noted that the optics of moving bodies would require the separation of ether and matter. In August 1899 upon reading Hertz, Einstein wrote Mileva Marić:

I am more and more convinced that the electrodynamics of moving bodies in today's formulation [*Darstellung*] does not agree with the truth, that a simpler formulation will be possible. The introduction of the name 'ether' in the electric theories has led to the idea of a medium whose motion can be spoken about, although I do not think we can attach a physical meaning to this way of speaking. I believe that electric forces can be directly defined only in empty space. Further, we will have to conceive electric currents not as 'the vanishing in time of electric polarization' but as the motion of true electric masses, the reality of which the electrochemical equivalents seem to prove . . . Electrodynamics would then be the science of the motions in empty space of moving electric and magnetic masses. The radiation experiments should tell us which of the two pictures [of the electric current] must be chosen.

"The electrodynamics of moving bodies in today's formulation" is a reference to Hertz's theory with its fully dragged ether. Einstein joins Drude in rejecting ether motion, and Helmholtz in reducing electric currents to the circulation of electric masses. The resulting picture is that of electric particles moving through "empty space." This expression and "the name ether" suggest that Einstein rejected any mechanical or naively substantial ether. It will be clear from subsequent letters that he did not exclude a more abstract ether in Drude's sense. The picture he had in mind resembled Lorentz's stationary ether coupled with ions or electrons moving through it. At that time he was probably unaware of Lorentz's theory and he knew little or no optics of moving bodies (this topic was not taught at the ETH, and he does not seem to have read on it before 1899).<sup>46</sup>

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<sup>46</sup> Drude 1894; Helmholtz 1893; Hertz 1892; Einstein to Marić, 10? Aug. 1899, *ECP* 1, pp. 225–227.

It is not clear what kind of "radiation experiment" Einstein had in mind to test his views. Possibly, he already conceived the experiment of the Kyoto lecture, comparing the intensities of the light emitted by the same source in two opposite directions. Indeed, his stationary ether, unlike Hertz's fully dragged ether, implies the anisotropy of light propagation on earth. From his next letter to Marić, we know he also planned an experiment of Fizeau's kind: he had "a good idea to investigate which effect the relative motion of bodies with respect to the ether has on the velocity of propagation of light in transparent bodies." Possibly, he was not yet aware of Fizeau's experiment, and he was reinventing it as a test between his stationary ether and Hertz's fully dragged ether. Einstein also mentioned he had a plausible theory for this effect, perhaps something like one of Lorentz's derivations of the Fresnel drag.<sup>47</sup>

#### D2: *A first piece on relative motion* (1899)

Einstein then wrote a piece on "the relative motion of the ether with respect to ponderable matter," and showed it to his "principal" at the ETH, Heinrich Weber, who reacted "like a mother in law" (*stiefmütterlich*). Weber was probably aware of Lorentz's theory, which had recently received much publicity at the *Naturforscherversammlung* of 1898 in Düsseldorf, and he was therefore unimpressed by Einstein's ill-informed proposal. Perhaps under Weber's recommendation, Einstein read Willy Wien's Düsseldorf address on ether motion, which he found "very interesting." Wien there summarized the results of numerous ether-drift experiments, including Fizeau's experiment of 1851 and the Michelson-Morley experiment of 1887. About the latter, he wrote: "If the ether is at rest, the time that a light ray needs to travel back and forth between two glass plates must change when the plates move. This change is of the order  $u^2 / c^2$ ,

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<sup>47</sup>Einstein to Marić, 10 Sep. 1899, in *ECP* 1, pp. 229–230. On Einstein's ether-drift experiments, see Stachel 1987.

but should be observable by interference." Wien briefly characterized Lorentz's theory as based on invariable ions in a stationary ether, stated the correspondence theorem according to which to first order in  $u/c$  the laws of propagation of light in a system of bodies moving at the velocity  $u$  in the ether are the same as the laws in a system at rest provided the true time is replaced with Lorentz's local time. Wien also mentioned the attempts to explain the negative-result of the Michelson-Morley experiment through the Lorentz contraction in a stationary ether.<sup>48</sup>

### D3: *Toward a "capital memoir"* (1901)

Einstein kept working on the electrodynamics of moving bodies, although thermal and kinetic-molecular physics then occupied most of his time. In March 1901, he wrote to Marić about the near completion of "our work on relative motion." In April, he discussed "the principal separation of ether and matter and the definition of absolute rest" with his friend Michele Besso. In September, he told Grossmann he now had "a much simpler method for investigating the relative motion of matter with respect to the ether . . . based on ordinary interference experiments." This might have been a variant of Michelson's second-order experiment of 1887. In December, Einstein told Marić that he was "working hard on an electrodynamics of moving bodies that promises to yield a capital memoir" and that his doctoral adviser Alfred Kleiner had encouraged him to publish the theory and the attached experimental method. Lastly, Einstein mentioned his intention to read what Lorentz and Drude had written on this topic. The promised memoir never came out.<sup>49</sup>

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<sup>48</sup> Einstein to Marić, 28? Sep. 1899, *ECP* 1, pp. 233–235; Wien 1898, p. XV.

<sup>49</sup> Einstein to Marić, 27 Mar. 1901, *ECP* 1, p. 282; 4 Apr. 1901, p. 285 (Besso); 17 Dec. 1901, p. 325 (capital memoir); 19 Dec. 1901, p. 328 (Kleiner); 28 Dec. 1901, p. 330 (Lorentz and Drude); Einstein to Grossmann, 6? Sep. 1901, p. 316. Drude's *Lehrbuch der Optik* (1900) had a chapter (II:8) on Lorentz's optics of moving bodies.



There is no evidence that in this project Einstein adopted the relativity principle. The expression "our work on relative motion" in the letter to Marić should not be read as work based on the relativity principle, since other extracts indicate he meant motion relative to the ether. The letter to Besso alludes to the separation of ether and matter and the ether qua absolute space, not to the elimination of the ether. The letter to Grossmann indicates that in the fall of 1901 he was still interested in testing effects of the motion of matter through the ether. It is not entirely impossible that, in agreement with Wertheimer's account and with Einstein's late recollections, he was betting for a negative result of such tests. But it is more likely that, having not yet paid much attention to the Michelson-Morley experiment, he still admitted the possibility of second-order effects of the earth's motion through the ether. In this event, his promised "capital memoir" would still be based on the stationary ether and nearing an optics of moving bodies similar to Lorentz's. This would explain why this memoir never came out: while studying Lorentz *Versuch* in 1902, he would have realized that most of his considerations had been either anticipated or refuted. Three years elapsed before he arrived at his theory of relativity. Unfortunately, there are very few traces of intermediate reflections. All we know, from a letter to Besso, is that in January 1903 he was planning "comprehensive studies in electron theory."<sup>50</sup>

### *Synthetic remarks*

The information from Einstein's letters is much too scarce to allow a precise reconstruction of Einstein's path toward special relativity. However, it gives us valuable information on Einstein's earliest views on the electrodynamics of moving bodies and on their sources. It can also be used to confirm or refute components of Einstein's (alleged) descriptions of his path of discovery.

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<sup>50</sup> Einstein to Besso, 22? Jan. 1903, *ECP* 5, p. 10. See Stachel et al., *ECP* 2, p. 258–261.

Firstly, the letters confirm that Einstein originally adopted a stationary ether and conceived optical tests of the motion of the earth through this ether, in agreement with most of the G accounts and also with H1 and H2. What cannot be firmly decided from the letters is the extent to which Einstein expected a positive result of these tests. All I can say is that the phrasing of Einstein's mentions of such tests suggests he wanted evidence for the stationary ether.

Secondly, one letter confirms Einstein's interest in an experiment of the Fizeau kind, testing how the motion of a transparent body affects the velocity of light through it. When, probably while reading Wien in 1899, Einstein became aware of Fizeau's result, he must have welcomed it as a confirmation of his stationary ether, in agreement with most of the G accounts.

Thirdly, in one letter of 1899 Einstein mentions reading a "very interesting" article in which Wien reviewed the question of ether motion and referred to the Michelson-Morley experiment. Against some of Einstein's late recollections, it cannot be doubted that he was aware of this experiment by the fall of 1899. However, owing to the sketchy character of Wien's description, he may not have fully realized the import of this result before studying Lorentz's *Versuch* in 1902.

Unfortunately, Einstein's correspondence gives us no clue on when and why he adopted the relativity principle and required the laws of the theory to have the same form in any inertial frame. There is no mention of the Michelson-Morley experiment, no mention of the electromagnetic-induction argument. The contents of the "capital memoir" Einstein planned in 1901 remain mysterious. If we believe Einstein's statement in H1 that he adopted the relativity principle around the time of his studying Lorentz's *Versuch* (in early 1902), then this memoir was not based on the relativity principle and probably still relied on the stationary ether.

## 6. Putting the pieces together

As we have seen, the G, H, and D sources often confirm or complement each other, and sometimes contradict each other. Of course, the direct sources D must be given precedence when they conflict with the G or H sources. The G sources may be affected by a posteriori rationalization of the genesis of the theory, and the H sources suffer from their sketchy and processed character, not to mention Einstein's memory failures in the latest recollections. When a conflict occurs among the G sources, among the H sources, or between the G and H sources, and when D is not sufficient to decide the issues at stake, we may still be able to resolve this conflict by appealing to internal consistency, background knowledge, or distortion tracking. This is what we have done piece by piece in the synthetic remarks at the end of the three previous sections.

Having solved or at least attenuated the contradictions, we may now put all the pieces together and construct a synthetic narrative that combines the three kinds of sources for the genesis of Einstein's special relativity:

*After reading Drude, Helmholtz, and Hertz on electrodynamics in his first ETH years, Einstein concluded that the electrodynamics of moving bodies should be based on the motion of electric particles (ions and electrons) through a stationary ether. Like Helmholtz, he believed that fundamental electrodynamics and optics should integrate the atomistic character of matter and electricity. Like Drude and Hertz, he rejected any attempt of explain the internal states of the ether mechanically. Like Drude, he rejected Hertz's idea of an ether dragged by matter, for in his eyes a non-mechanical ether could not have velocity. He still believed in the reality of the ether*

*and conceived optical effects of the motion of the earth through the ether, for instance a difference of intensity for the light emitted by a terrestrial source in opposite directions. Another way he imagined to decide between his stationary ether and Hertz's fully dragged ether was a measurement of the velocity of light in moving transparent matter.*

*By the fall of 1899, through his teachers and by reading a review of ether motion by Wien, he knew that Lorentz had already developed a theory based on electrified particles moving in a stationary ether, he knew that Fizeau had already proved that the ether was not fully dragged by matter, and he also knew that Michelson had failed to observe differences in the round trips of light in two different directions. From then on he regarded Fizeau's result as a major confirmation of the stationary ether (the partial drag of the waves been explained through the motion of the center of secondary waves in the moving dielectric). But he did not yet take Michelson's null result for granted, and he did not yet study Lorentz's writings. Instead, in the two following years he developed his own electrodynamics of moving bodies in partial collaboration with Marić, and he imagined his own interferential test of the earth's motion through the ether. Presumably, Einstein's theory then resembled Lorentz's, and his planned experiment was similar to Michelson's. The "capital memoir" that was supposed to gather these results never appeared. The probable cause of this abandonment was Einstein's study of Lorentz's Versuch in 1902. He then realized that much of his theory had been anticipated by Lorentz and that Michelson's null result was firmly established.*

*Yet Einstein disliked the way Lorentz accounted for this null result. In his mind, a symmetry found in nature, here the equivalence of all inertial frames with respect to optical experiments, should find a direct expression in the theory. In contrast, Lorentz artificially compensated the theoretical anisotropy of light propagation with the Lorentz contraction. Note*

*that Einstein's criticism (unlike Poincaré's) was not that the contraction could not be justified in Lorentz's theory (in fact it could be by assuming the quasi-electromagnetic character of all molecular forces). It was part of a broader criticism in which he deplored, in the stationary-ether theories, the existence of theoretical asymmetries without phenomenal counterpart. A first simple example was magnet-coil induction, which is caused by an electric field when the magnet moves in the ether, by a magnetic field when the coil moves in the ether. Another was the null result of all first-order ether-drift experiments, which Lorentz explained through an asymmetric compensation mechanism: a local time shift compensated the lack of Galilean invariance of the Maxwell-Lorentz equations. Originally, Einstein, like most of his contemporaries, tolerated the theoretical asymmetries as long as he could conceive observable effects of these asymmetries in finer phenomena. In 1902, he changed his mind and adopted the relativity principle in the strong sense that the theoretical expression of physical laws, not only the observed phenomena they purport to explain, should be the same in any inertial frame.*

*At this point Einstein did not see how to progress without fundamentally departing from Lorentz's theory. Indeed, these equations imply the constancy of the velocity of light in the ether frame, and its variability in any other frame. The Maxwell-Lorentz equations had to be given up or at least they had to be used in a fundamentally different way, without the supporting ether. The main option Einstein then considered was an emission theory in which the velocity of the source adds to the velocity of the emitted radiation. After a while he gave up this theory for a variety of reasons: there was no wave equation for its fields, the light of an accelerated source could strangely back up on itself, and the usual parameters of intensity, frequency, and polarization were no longer sufficient to characterize a light beam. After all, Einstein now decided, the velocity of light had to be a constant independent of the motion of the source, as it*

*was in Lorentz's theory in the ether frame. For a long time, Einstein just did not know how to reconcile this light principle with the relativity principle.*

*From Lorentz, Einstein knew that the lack of Galilean covariance could be compensated by a local time shift and a field transformation—at first order in the Versuch Einstein read. In Lorentz's eyes, this compensation was only a formal artifice, and its connection with the first-order invariance of optical phenomena was only indirect. However, if one forgets the time shift, the transformed fields are easily seen to be the fields measured by an observer in the moving frame. Then one may wonder whether the shifted local time might not also be the time measured by moving observers. In the spring of 1905, Einstein suddenly realized that this was indeed the case if the clocks of the moving frame were synchronized through light signals and if the constancy of the velocity of light was assumed in this process. Namely, two clocks thus synchronized in the moving frame appear to be desynchronized in the ether frame, to the extent  $ux / c^2$  if  $u$  denotes the velocity of the moving frame and  $x$  the distance of the two clocks in the direction of this velocity.*

*There being no detectable difference between the ether frame and the moving frame in this reasoning, Einstein just eliminated the ether and assumed the complete equivalence of all inertial frames. The seeming incompatibility of the light principle and the relativity principle now appeared to result from a neglect of the role that the velocity of light plays in defining the time of synchronized clocks. Under the new definition of time, time became frame-dependent, the Lorentz transformation replaced the Galilean transformation of space and time coordinates, and velocities had to be "added" according to a new rule in which any velocity added to the velocity of light still gave the velocity of light. The Maxwell-Lorentz equations turned out to be invariant*

*under the new coordinate transformations supplemented with fitting field transformations. This symmetry directly implied the observed invariance of optical and electrodynamic phenomena.*

Although this narrative is fuller and richer than the G, H, D sources would separately allow, it still has gaps and uncertainties. We can imagine ways to complete it and sharpen it. One obscure point is the time and way in which the electromagnetic-induction argument entered Einstein's thought. I believe it was contemporary to Einstein's adoption of the relativity principle because Einstein's conception of this principle entails the kind of theoretical invariance he promotes in this argument. John Norton speculates that Einstein early used this argument to explore a Galilean covariant electrodynamics in some approximation, with different fields in different frames. Robert Rynasiewicz, Jürgen Renn, and other scholars instead try to relate Einstein's idea of the relativity principle to his reflections on the nature of radiation, for instance by arguing that both elude the ether and make radiation a self-contained entity, or by emphasizing a common principle-based approach. Peter Galison makes Einstein's optical definition of simultaneity depend on his familiarity with the technological distribution of time through his patent work in Bern. Alberto Martínez integrates Einstein's new kinematics in a long tradition of discussing the concept of motion in mechanical context.<sup>51</sup>

Another way to complete the synthetic narrative is to point to authors from which Einstein may have borrowed more than his writings and sayings suggest. The most plausible candidate is Poincaré, because the French mathematician, independently of Einstein and before Einstein, arrived at a different version of relativity theory. None of the G, H, D sources gives Poincaré a significant role in Einstein's reflections. Poincaré is mentioned only in regard to the

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<sup>51</sup> Norton 2004; Rynasiewicz 2000; Rynasiewicz and Renn 2006; Galison 2003; Martínez 2009.

role of rigid bodies in the conceptual analysis of space, also for a momentum-balance equation that Einstein used in 1906 in a derivation of the mass-energy equivalence. Nowhere does Einstein mention that in a book he devoured with his friends of the Akademie Olympia, *La science et l'hypothèse* (1902, 1904 for the German translation), Poincaré offered a criticism of simultaneity, introduced the relativity principle as a general principle of all physics, and reproached Lorentz with satisfying this principle only in the manner of successive approximations. Nor does Einstein mention that in the memoir of 1900 in which Einstein found the momentum equation he used in 1906, Poincaré interpreted Lorentz's local time and corresponding fields as the time and fields measured by moving observers who synchronize their clocks optically under the convention of constant light velocity.<sup>52</sup>

It is nonetheless conceivable that Einstein consciously or unconsciously borrowed the optical interpretation of Lorentz's local time from Poincaré, and then turned this interpretation into a definition. It is also conceivable that reading Poincaré (*La science et l'hypothèse* or his widely diffused address of 1900 at the international congress of physics in Paris) helped Einstein adopt the relativity principle. In this regard, it should be remarked that against Einstein's assertion in his G and H accounts, the Michelson-Morley did not convince all physicists of the general truth of the relativity principle. On the contrary, Poincaré, Bucherer, and Einstein were the only physicists to adopt this principle in electrodynamics before 1905. Moreover, the very name "relativity principle" appeared for the first time under Poincaré's pen in *La science et l'hypothèse* (1902) beyond the mechanical context in which similar names had already been used in France.<sup>53</sup>

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<sup>52</sup> Poincaré 1902, 1904, 1900a; Einstein 1906. On the Poincaré-Einstein connection, see Fölsing 1993, §II.10.

<sup>53</sup> Poincaré 1902, p. 281.



These various attempts to connect the dots in Einstein's pathway to relativity contradict each other. For instance, the alleged cause of Einstein's redefinition of time varies considerably. For Fölsing, it was Besso telling Einstein about Poincaré's interpretation of Lorentz's local time; for Galison, it was immersion in Swiss time technology and the distribution of time; for Norton it derived from the desire to extend a Galilean-invariant formulation of electrodynamics; for Martínez, it was an unusual attention to the kinematics of rigid bodies as a precondition for any dynamics. My synthetic narrative is largely compatible with these more speculative attempts. Being based on Einstein sources, it has the inconvenient of making the genesis of special relativity an Einstein-centered story with little context. Provided we can trust these sources as much as I have argued in this essay, it has the advantage of explaining much of Einstein's original pathway without entering controversial grounds.

### **Appendix 1: The Fresnel drag and the laws of refraction on earth**

Let light travel through a series of transparent substances all at rest on earth. According to an extension of Fermat's principle, the trajectory of this light between two fixed points (on earth) is that for which the traveling time is a minimum, whether the medium of propagation (the ether) is at rest or not. The velocity of light with respect to the ether in a substance of optical index  $n$  is  $c/n$  (whether or not the substance is moving in absolute space), if  $c$  denotes the velocity of light. The absolute velocity of the ether across this substance is  $\alpha \mathbf{u}$ , where  $\alpha$  is the dragging coefficient and  $\mathbf{u}$  is the velocity of the earth (with respect to the remote, undisturbed parts of the ether). Therefore, the velocity of light along the element  $d\mathbf{l}$  of an arbitrary path is

$c/n + (\alpha - 1)\mathbf{u} \cdot \mathbf{dl} / ds$  with respect to the substance (with  $ds = \|\mathbf{dl}\|$ ). To first order in  $u/c$ , the time taken by light during this elementary travel is

$$dt = (n/c)ds + (n^2/c^2)(1 - \alpha)\mathbf{u} \cdot \mathbf{dl}.$$

Note that the index  $n$  and the dragging coefficient  $\alpha$  in general vary along the path, whereas the velocity  $\mathbf{u}$  has the same value (the velocity of the earth) for the whole optical setting. The choice  $\alpha = 1$  (complete drag) leaves the time  $dt$  and the trajectory of minimum time invariant, as should obviously be the case. Fresnel's choice,  $\alpha = 1 - 1/n^2$ , yields

$$dt = (n/c)ds + (1/c^2)\mathbf{u} \cdot \mathbf{dl},$$

so that the time taken by light to travel between two fixed points of the optical setting differs only by a constant from the time it would take if the earth were not moving. Therefore, the laws of refraction are unaffected (to first order) under Fresnel's assumption.<sup>54</sup>

## Appendix 2: Maxwell-Lorentz equations, local time, and Lorentz transformations

For the microscopic fields  $\mathbf{e}$  and  $\mathbf{b}$  and in Hertzian units, the Maxwell-Lorentz equations read

$$\begin{aligned}\nabla \times \mathbf{e} &= -c^{-1} \partial \mathbf{b} / \partial t, \quad \nabla \times \mathbf{b} = c^{-1} [\rho_m \mathbf{v} + \partial \mathbf{e} / \partial t], \\ \nabla \cdot \mathbf{e} &= \rho_m, \quad \nabla \cdot \mathbf{b} = 0, \\ \mathbf{f} &= \rho_m [\mathbf{e} + c^{-1} \mathbf{v} \times \mathbf{b}],\end{aligned}$$

where  $\rho_m$  denotes the microscopic charge density (within the ions),  $\mathbf{v}$  the velocity of the ions (or electrons), and  $\mathbf{f}$  the density of the force acting on the ions. These equations are valid in the reference frame of the stationary ether. For electromagnetic phenomena on the earth, which is

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<sup>54</sup> See Mascart 1893, Vol. 3, Chap. 15.

moving at the velocity  $\mathbf{u}$  in the ether, Lorentz performed the Galilean transformation  $\mathbf{r} \rightarrow \mathbf{r} - \mathbf{u}t$ .

The resulting field equation contains new  $\mathbf{u}$ -dependent terms. As Lorentz realized in 1892, these terms disappear to first order in  $u/c$  if the time coordinate is shifted and the fields are transformed according to

$$t' = t - \mathbf{u} \cdot \mathbf{r} / c^2, \quad \mathbf{e}' = \mathbf{e} + c^{-1} \mathbf{u} \times \mathbf{b}, \quad \mathbf{b}' = \mathbf{b} - c^{-1} \mathbf{u} \times \mathbf{e}.$$

In 1899 and 1904, Lorentz generalized this result to any order in  $u/c$  thanks to the transformations

$$\begin{aligned} \mathbf{r}' &= \varepsilon(\gamma, 1) \mathbf{r}, \quad t' = \varepsilon(\gamma^{-1} t - \gamma \mathbf{u} \cdot \mathbf{r} / c^2), \\ \mathbf{e}' &= \varepsilon^{-2}(1, \gamma)(\mathbf{e} + c^{-1} \mathbf{u} \times \mathbf{b}), \quad \mathbf{b}' = \varepsilon^{-2}(1, \gamma)(\mathbf{b} - c^{-1} \mathbf{u} \times \mathbf{e}), \end{aligned}$$

where  $\varepsilon$  is an undetermined constant (for a given value of  $u$ ) and the factor  $(1, \gamma)$  means a multiplication by 1 of the component of the following vector parallel to  $\mathbf{u}$  and a multiplication by  $\gamma \equiv (1 - u^2 / c^2)^{-1/2}$  of the component perpendicular to  $\mathbf{u}$ . The transformations obtained by combining the latter transformation with the Galilean transformation,

$$\begin{aligned} \mathbf{r}' &= \varepsilon(\gamma, 1)(\mathbf{r} + \mathbf{u}t), \quad t' = \varepsilon\gamma(t + \mathbf{u} \cdot \mathbf{r} / c^2), \\ \mathbf{e}' &= \varepsilon^{-2}(1, \gamma)(\mathbf{e} - c^{-1} \mathbf{u} \times \mathbf{b}), \quad \mathbf{b}' = \varepsilon^{-2}(1, \gamma)(\mathbf{b} + c^{-1} \mathbf{u} \times \mathbf{e}), \end{aligned}$$

leave the Maxwell-Lorentz field equations exactly invariant, as Poincaré and Einstein proved in 1905. Poincaré called them "the Lorentz transformations." He and Einstein derived  $\varepsilon = 1$  by symmetry arguments.

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The following abbreviations are used: *ACP*, *Annales de chimie et de physique*; *AHES*, *Archive for the history of exact sciences*; *AJP*, *American journal of physics*; *AN*, *Archives néerlandaises des sciences exactes et naturelles*; *AP*, *Annalen der Physik*; *BB*, Königlich Preußische Akademie der Wissenschaften zu Berlin, mathematisch-physikalische Klasse, *Sitzungsberichte*; *CR*, Académie des sciences, *Comptes-rendus hebdomadaires des séances*; *ECP*, *The collected papers of Albert Einstein* (Princeton: Princeton University Press); *HSPS*, *Historical studies in the physical (and biological) sciences*; *HWA*, Hermann von Helmholtz, *Wissenschaftliche Abhandlungen*, 3 vols. (Leipzig: Barth, 1882, 1883, 1895); *LCP*, Hendrik Antoon Lorentz, *Collected papers*, 9 vols. (The Hague: Nijhoff, 1934–1939); *PM*, *The philosophical magazine*; *PRA*, Royal Academy of Amsterdam, *Proceedings*; *PZ*, *Physikalische Zeitschrift*; *SHPMP*, *Studies in history and philosophy of modern physics*; *VKA*, Koninklijke Akademie van Wetenschappen, Amsterdam, *Verslagen*.

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