Dismissing renewed attempts to deny Einstein the discovery of special relativity

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On the occasion of the centenary of special relativity, several publications have argued that Poincaré, and not Einstein, was the discoverer of special relativity. Attacks have simultaneously been directed at Einstein, whose 1905 article on the electrodynamics of moving bodies was alleged to be a forgery. These attacks praise Lorentz and Poincaré for their results and neglect Poincaré's failure to make the necessary conceptual leap and understand the fundamental consequences of the principle of relativity. I identify what was missing in Lorentz's and Poincaré's views and contrast them with Einstein's insights.
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I. SPECIAL RELATIVITY: CONCEPTS AND CONSPIRACY

We have recently celebrated the centenary of the fascinating developments in physics that were the direct consequence of the immense achievements of two giants of science, Isaac Newton and James Clerk Maxwell. Their work was pursued along two distinct paths by two other giants, Henri Poincaré and Albert Einstein.

At the end of the nineteenth century, Newton's laws of motion, together with the necessary masses and forces, were believed to be what "God created,"[1] from which all natural phenomena would follow by deduction provided that appropriate methods could be developed. The successes that were achieved by nineteenth-century physicists confirmed their belief that classical mechanics provided "a firm and definitive foundation for all physics, indeed for the whole of natural science."[1] As a consequence, they attempted to base Maxwell's theory of electromagnetism on mechanical models as well.

The extent of some of the problems posed by this attempt—problems that had to wait the general theory of relativity for a partial solution—can be understood from the fact that Newton had to postulate instantaneous forces acting at a distance, in contrast to those appearing in Maxwell's theory, which propagate at the speed of light.

Almost all physicists attribute the discovery of special relativity to Albert Einstein, although claims have periodically been made since the publication of Edmund Whittaker's monograph[2] that priority in the field belongs either to the mathematician Henri Poincaré alone or to Poincaré and the physicist Hendrik-Antoon Lorentz. The debate was reopened in 1994 by an article in La Jaune et la Rouge, the journal of the alumni of the Ecole Polytechnique in Paris, of which Poincaré was an alumnus. The author, Jules Leveugle,[3] attributed all of special relativity to Lorentz and Poincaré, especially to the latter. In particular, he attributed the equivalence between the inertial mass m and energy E of a body, that is, the relation $E=mc^2$, where c is the speed of light to Poincaré. The latter claim recalls the attribution of this discovery to the German physicist Hasenhörl. The assertion[4] in Annalen der Physik in 1921 of the latter's priority by the Nobel Prize winner Philipp Lenard, who was to become a rabid proponent of the Third Reich, was part of the efforts to discredit Einstein.[5–7] This assertion met with an energetic retort in the same journal by Max von Laue.[8] Laue received the Nobel Prize for Physics in 1914 for the discovery of the diffraction of x rays by crystals. He distinguished himself by his courageous views under the Third Reich.

Leveugle's campaign in praise of Poincaré was conducted in association with Christian Marchal,[9] also an alumnus of the Ecole Polytechnique, and with Anatoly Logunov,[10] a member of the Academy of Sciences in Moscow. It included accusations by Leveugle[11] of plagiarism on the part of Einstein. Similar attacks by others, directed at all of Einstein's scientific activity including general relativity, were then made in the press and on the Internet[12–14] and in books.[15–17] Many of the attacks on Einstein concerning general relativity focus on the race that took place in November 1915 between Einstein and the mathematician David Hilbert to formulate the equations of the general theory,[12,15,18] and are not within the scope of this paper.

I shall concentrate on Leveugle's arguments, which focus on how special relativity came into being. The arguments of Leveugle and his associates go as follows: (a) Lorentz[19] and Poincaré[20,21] discovered that Maxwell's equations of electromagnetism are covariant with respect to changes in a reference frame under uniform rectilinear translation and demonstrated the group properties of the transformations.[9,10,22] (b) There is nothing more in Einstein's publications than in those of Lorentz and Poincaré, except relativistic Doppler and stellar-aberration effects.[23] (c) The decisive step attributed by most physicists to Einstein is but a variant of Poincaré's work.[24] Alternatively, the attribution of the decisive step to Einstein by Louis de Broglie follows from de Broglie's lack of a thorough reading or of understanding relativity.[25]

Leveugle's fundamental argument is that Einstein's "founding" article[26] was a forgery,[27] from which he draws two conclusions, depending on how the forgery allegedly occurred. One theory, which has also been stated by others outside Leveugle's group,[13,14,17,18] is plagiarism. Leveugle's book[16] formulates the second theory, namely, that there was a conspiracy hatched to Einstein's advantage and with his approval by some of the greatest German scientists of his time, notably Max Planck. Leveugle's book is of special interest because it brings into play, among other leading French scientists, a close colleague of Poincaré, the physicist Paul Langevin.

Leveugle starts by examining the conditions under which their ideas came to Lorentz and Poincaré and remarks that the dialog between these two great minds was not to succeed until after ten years of effort. Then he states his bias: "Any-one knowing the steps followed by Poincaré and Lorentz between 1895 and 1905 cannot believe that the theory could have sprung suddenly, fully finalized from the mind of a single scientist, and precisely in the middle of 1905."[27]

Another implication is present in Leveugle's theory, similar to that found in a text by de Broglie, although de Broglie leaves no doubt as to whom he considered to be the discoverer of (special) relativity[28]:

> "It could therefore very easily have been Henri Poincaré, and not Einstein, who first developed the theory of relativity in all its generality, which would have attributed the honor of this discovery to French science."

In his 1994 article[29] Leveugle accused Einstein of copying Poincaré's 1905 note,[20] of which Einstein allegedly had knowledge due to his position at the Bern Patent office. If true, Einstein would have had to copy the note in the time between the oral presentation in Paris on June 5, 1905 of the note and the receiving of Einstein's manuscript on June 30, 1905 by Annalen der Physik. This 25-day interval needs to be further reduced by the time taken to print Poincaré's note and to mail these two texts. In 2004 Leveugle admitted that there were weaknesses in his plagiarism theory,[30] and he now preferred a conspiracy theory that postulates the existence of a group of German scientists, who rapidly wrote an article after Poincaré's note of June 1905 was received. According to Leveugle, one piece of evidence stems from the absence of a summary of Poincaré's 1905 note in the collection of summaries published in Beiblätter zu den Annalen der Physik "over which Planck had editorial control." As to the motive, it is clear: "For the scientists of the University of Göttingen it was unthinkable to let a Dutchman, much less a Frenchman, enjoy the reward of a major discovery they had been chasing after for years."

The main designer of the plot was David Hilbert, who was jealous of Poincaré and dragged into the plot Max Planck and the Annalen der Physik. The team allegedly included Minkowski and probably von Laue.

This theory suffers from two weaknesses in particular. Like other conspiracy theories, it requires the team of manipulators to gain the cooperation of associates. Leveugle is aware that French physicists and mathematicians of the time must at least have supported the manipulation.[31] The role assigned to Einstein is that of a front man, who was selected to sign the article that was written by the team. Einstein was the ideal front man, both as a Swiss citizen, and because Planck had earlier recognized his propensity to steal ideas from others.

The most direct response to these theories is to show the nature of Poincaré's ideas and approach that prevented him from producing what Einstein achieved. We will do so by referring to the publications of Einstein and Poincaré and comments by scientists and science historians. Among the scientists are three Nobel Prize winning physicists, whose work was radically influenced by the theory of relativity. Two of them wrote well known monographs.[32,33] We will see that some of Poincaré's writing was very close to relativistic thinking,[34] and yet on the most crucial issue, it was very far away. In contrast, Einstein's thinking, based on strikingly simple, but far-reaching remarks, appears straightforward. In various biographies and studies describing Einstein's work are epistemological analyses, accompanied in some cases by extracts from articles and documents of the period, such as letters exchanged with colleagues and friends.[5,35–37] The collected papers of Einstein are a particularly valuable source of information and commentary.[38] Books and articles on the development of special relativity include the works by Gerald Holton and Arthur Miller and more recent ones by John Norton[39] and Michel Janssen,[40] who emphasized Einstein's determination to implement the relativity principle in electrodynamics, and his fondness for theories of principle. Einstein's motivations in developing special relativity were astutely analysed by Robert Rynasiewicz.[41–43]

II. POINCARÉ

The first generalization of the Galilean-Newtonian relativity principle is due to Poincaré[44]:

> "The laws of physical phenomena should be the same whether for a fixed observer or for an observer carried along in a uniform movement of translation."

According to the relativity principle, the natural laws are invariant with respect to a change of coordinate system among an infinite set of preferred systems, in uniform translational motion relative to one another. These reference bodies, all equivalent with respect to the formulation of natural laws, are the inertial frames in which Galileo's law of inertia is valid.

However, the generalized principle remained a conjecture for Poincaré. The conjectural nature of Poincaré's relativity principle has been analyzed by Holton[45] and Miller.[46] This conjectural nature is emphasized here because it is very likely the reason why Poincaré did not find the ultimate consequences of the relativity principle. It has often been said that Poincaré's handicap was his "conventionalist epistemology"[28,46,47] "which granted the laws of geometry and physics at most the nature of a useful convention, without a meaning of deeper reality."[48] For Poincaré differing mathematical representations of the universe could constitute equivalent conventions.

Louis de Broglie wrote that[49]

> "[…] Poincaré did not take the decisive step. He left to Einstein the glory of having perceived all the consequences of the principle of relativity and, in particular, of having clarified through a deeply searching critique of the measures of length and duration, the physical nature of the connection established between space and time by the principle of relativity."

Another aspect of the controversy concerns Lorentz's coordinate transformations. As mentioned in Sec. I, Lorentz and Poincaré demonstrated that these transformations ensure the covariance of Maxwell's equations with respect to the changes in the reference frame resulting from a uniform rectilinear translation. In reference to the covariance of Maxwell's equations, Wolfgang Pauli stressed the need to develop a new theory and described Einstein's solution in the following terms (the italics are Pauli's)[50]:

> "[…] Lorentz and Poincaré had taken Maxwell's equations as the basis of their considerations. On

the other hand, it is absolutely essential to insist that such a fundamental theorem as the covariance law should be derivable from the simplest possible basic assumptions. The credit for having succeeded in doing just this goes to Einstein. He showed that only the following simple axiom in electrodynamics need be assumed: *The velocity of light is independent of the motion of the light source*."

The author index of Pauli's article, which he wrote at the age of 21 for the Encyclopädie der mathematischen Wissenschaften, contains 18 entries under Poincaré. Another remark made by Pauli in this article clarifies what was one of Einstein's central ideas, and we shall return to it in the following section:

> "Actually the mechanistic concept of an ether had already come to be superfluous and something of an hindrance when the elastic-solid theory of light was superseded by the electromagnetic theory of light. In this latter the ether substance had always remained a foreign element."

"Hindrances" appear when one follows Lorentz and Poincaré in their considerations of *local time*, which is a *fictitious time*, or on the *contraction* that moving objects were thought to undergo from the mere fact of their movement relative to the ether. Marie-Antoinette Tonnelat, the author of many papers and studies on relativity, wrote about Lorentz's fictitious time[51]:

> "Naturally this fictitious time appears through experience, but it remains nonetheless artificial in the sense that at any moment one can set it against the "true," "absolute" time which characterizes the system of the ether. The role of local time is thus above all to preserve the formalism of the propagation equations in any system of reference. It is a mathematical "artifice." It is an artifice because at any moment one can set against it a true and nonetheless accessible time, that of the ether [...].
>
> Poincaré's own contribution, moreover, tends to endorse this point of view. In his 1904 memoir, he shows that this fictitious time would actually be the one that local clocks would indicate, co-ordinated by signals with clocks of the ether marking absolute time. Nevertheless, this time remains fictitious, always comparable to the time of the ether, which remains true and absolute. Poincaré shows that the Lorentz transformations form a group, but they are interpreted in a completely classic way. The physical meaning of the theory does not succeed in linking up with what mathematics wants to make it express."

Lorentz and then Poincaré did suggest that Lorentz's coordinate transformations could be applied to forces of nature other than electromagnetic, although the physical meaning of those transformations remained unrecognized by both Lorentz and Poincaré. One of the most telling statements Poincaré made in this respect, dated 1908, when considering the contraction of moving objects (the italics are Poincaré's) is the following[52]:

> "This hypothesis, formulated by Lorentz and FitzGerald, will at first seem extraordinary; all we can say in its favor at the moment is that it is only the immediate translation of the experimental result obtained by Michelson, if we *define* lengths by the time light takes to traverse them."

The term "hypothesis" and the restriction in the comment, "all we can say in its favor," demonstrate that Poincaré's thinking stopped short of the crucial step, the one that makes the contraction of lengths and Michelson's experimental data follow from the principle of relativity and from the new conceptions of time and space that stem from it.

In a lecture given in April 1909 at Göttingen, Poincaré was more explicit about the preceding hypothesis; he called it "the third hypothesis,"[53] the first one being that the velocity of light is an upper limit, and the second the relativity principle. He maintained this stand throughout his life.[54]

Abraham Pais used the expression "Poincaré's third hypothesis" and drew the inescapable conclusion[55]:

> "It is evident that as late as 1909 Poincaré did not know that the contraction of rods is a consequence of the two Einstein postulates. Poincaré therefore did not understand one of the most basic traits of special relativity."

Leveugle's suggestion[56] that Poincaré intended the Lorentz transformations to be a postulate, containing an upper limit to velocities, does not help his position that Poincaré's "New Mechanics" is but a variant of special relativity, because this variant would require assumptions that were much more involved than those of Einstein;[57] postulating the Lorentz transformations does not bear the same semantic content as giving their physical interpretation.

Although Poincaré cannot be credited for having discovered special relativity, did he recognize the equivalence between inertial mass and energy of a body as Leveugle claims? Leveugle's claim[58] rests on the fact that in 1900 Poincaré obtained an expression for the quantity of motion of radiant energy[59] that agrees with the relation $E=mc^2$. Von Laue[60] paid tribute to Poincaré for this result, from which it follows that a charged particle in motion, for example, an electron, possesses an electromagnetic mass. These findings are far from Einstein's assertion of the general equivalence between inertia and energy.[61] The philosopher François L'Yvonnet, in a book of dialogs with the futurologist Thierry Gaudin,[62] has nonetheless followed the example of Leveugle and asserts that Poincaré "had very clearly formulated the relation $E=mc^2$." Both Gaudin and L'Yvonnet discuss why this relation, allegedly due to Poincaré, was attributed to Einstein: the latter's article was written in German (Gaudin[63]) and "Einstein perhaps had a greater sense of communication" (L'Yvonnet[63]).

If Poincaré had conceived $E=mc^2$ in 1900, his colleague Langevin would have known. Langevin had been closely following Poincaré's work, and both men spent a week traveling together in the United States after the St. Louis International Congress of Arts and Sciences in 1904.[64] Langevin would not have suddenly come a few years later to tell his co-worker Edmond Bauer that he was on track to find a relation between the inertial mass and the energy of a body.[65] He had checked it for an electron for which it followed from Lorentz's and Poincaré's work on radiation and was searching for a general theory. Bauer recounts that he was at the time in charge of abstracts for the journal Le Radium, and that he came across an article by someone named Einstein, where he saw the relation $E=mc^2$ that Langevin had been telling him about. He ran immediately to inform Langevin, without even reading the article.

We see that Poincaré may have had mathematical hints available to him for a major discovery in physics, that is, $E=mc^2$, without having even a suspicion of their significance.

In his 2004 book Leveugle emphasized that in Poincaré's 1900 example, the body emitting the radiant energy E loses the inertia $m=Ec^{-2}$. This addendum[66] by Leveugle to the $E=mc^2$ controversy leaves unchanged our last remark concerning Poincaré's lack of insight into certain aspects of the physics involved.

Poincaré's considerations on a body emitting radiant energy clearly show his unawareness of the equivalence between inertial mass and energy. He returned to the example of radiant energy in the lecture he gave at the International Congress in 1904 in St. Louis mentioned earlier and noted that the recoil of the emitting body occurred as if the projectile, that is, the radiant energy, were a "ball." However, as pointed out by Janssen,[67] Poincaré insisted that "our projectile here has no mass, it is not matter, it is energy."

III. EINSTEIN

Einstein's 1905 article on special relativity followed a period of almost ten years of study and personal inquiry to the extent of questioning some of the very foundations of physics. Some of his early questionings include the following:

(a) At the age of sixteen in the Swiss town of Aarau, Einstein came across the "Aarau paradox."[68] Imagine an observer moving at the speed of light, pursuing a beam of light. Theoretically he would observe "such a beam of light as a spatially oscillatory electromagnetic field at rest."[69] For the observer there would be no passing of time.

(b) Einstein was struck by the fact that Maxwell's electrodynamics led to "asymmetries which do not appear to be inherent to the phenomenon," as he stated in the introductory sentence of the 1905 article.[26]

(c) From the study of the Brownian motion of a freely moving mirror in a space filled with radiation,[70] Einstein concluded that the pressure of radiation that follows from Maxwell's equations cannot explain the average kinetic energy of the mirror as calculated from statistical mechanics.[71] This conclusion was another source of his dissatisfaction with existing electromagnetic theory, which he later summarized as:

> "[…] the defect of ascribing to matter and ether, on the one hand mechanical states, and on the other hand electrical states, which do not stand in any conceivable relation to each other."[72]

Such observations, combining considerations of great simplicity, and *gedanken* experiments with acutely perceptive analysis and the problems they posed convinced Einstein that neither mechanics nor electrodynamics could claim rigorous validity. He recounts how he thus came, shortly after Planck's 1900 discovery of energy quanta[73]:

> "[…] to the conviction that only the discovery of a universal formal principle could lead us to assured results."

This universal formal principle he found "by elevating the principle of relativity from a heuristic conjecture to a fundamental proposition."[74]

Einstein's crucial step was that he abandoned the mechanistic ether in favor of a new kinematics. He saw that the Lorentz group, required by electromagnetic theory, can be derived in all generality by kinematic arguments from the relativity principle, provided an experimental definition is given of the correspondence between times at different locations, based on the constancy of the velocity of light. Max von Laue described this crucial step at the celebration of Einstein's 70th birthday on March 14, 1949 (the italics are von Laue's)[75]:

> "In Lorentz's published work, his transformation yielded, next to absolute true time and absolute true space, other times and other space co-ordinates that, *as far as Maxwell's equations were concerned*, were equivalent to these "true" quantities. But they appeared as properties of the field of mathematics. Only Einstein took the step of justifying the equivalence of all these times and all these co-ordinates *for all natural phenomena*. No one before him had had this insight into the nature of space and time measures."

In Einstein's own account, given in correspondence exchanged with Carl Seelig on the occasion of the 50th anniversary of relativity, is what had been one of his concerns with prerelativistic physics[76]:

> "The new feature was the realization of the fact that the bearing of the Lorentz-transformations transcended their connection with Maxwell's equations and was concerned with the nature of space and time in general. A further result was that the Lorentz invariance is a general condition for any physical theory. This was for me of particular importance because I had already previously found that Maxwell's theory did not account for the micro-structure of radiation and could therefore have no general validity."

Einstein referred to his remark on pressure radiation, about which he wrote to Max von Laue in 1952, that it was what led him to the conclusion that[77]

> "[…] one has to assume rather that there exists a second type of pressure radiation, not derivable from Maxwell's theory, corresponding to the assumption that radiation energy consists of indivisible point-like localized quanta of energy $h\nu$ (and

> of momentum $h\nu/c$, c=velocity of light), which are reflected undivided. This way of looking at the problem showed in a drastic and direct way that a type of immediate reality has to be ascribed to Planck's quanta, that radiation must, therefore, possess a kind of molecular structure as far as energy is concerned, which of course contradicts Maxwell's theory."[78]

This discovery of the light quantum, which provided him with a "better understanding of blackbody radiation, fluorescence, the production of cathode rays, and other related processes connected with the emission or conversion of light," earned Einstein the 1921 Nobel Prize for physics and gave him more evidence for his understanding of the ether. He reviewed the problem of the ether in a lecture on "Ether and the theory of relativity," which he gave in 1920 at the University of Leyden. First, he described Lorentz's implementation of Maxwell's equations[79]:

> "As in empty space, so too in the interior of material bodies, the ether, and not matter viewed atomistically, was exclusively the seat of electromagnetic fields. […] Thus Lorentz succeeded in reducing all electromagnetic happenings to Maxwell's equations for free space."

Einstein went on to describe how the mechanistic concept of the ether as an elastic, imponderable medium, pervading all bodies and underpinning the electromagnetic field, was modified, first by Lorentz,[80] then by himself, transcending Lorentz's understanding[81]:

> "As to the mechanical nature of the Lorentzian ether, it may be said of it, in a somewhat playful spirit, that immobility is the only mechanical property of which it has not been deprived by Lorentz. It may be added that the whole change in the conception of the ether which the special theory of relativity brought about, consisted in taking away from the ether its last mechanical quality, namely, its immobility."

Special relativity was a radical change because, in the words of Einstein, the ether had become "superfluous."[26] There was no longer room for this peculiar idea present in the work of Lorentz and Poincaré that objects must undergo contraction by a dynamical effect resulting from their movement relative to the ether. In special relativity the relativistic contraction effect follows from only kinematics arguments.[26,82]

Although the ether of the nineteenth century was gone for good, Einstein encountered a new ether when he extended the relativity principle beyond inertial frames to coordinate systems that are in nonuniform motion relative to each other. Einstein realized the connection of this latter problem with that of the nature of gravitation and developed the general theory of relativity. In general relativity the state of the new ether is "at every place determined by connections with the matter and the state of the ether in neighbouring places, which are amenable to law in the form of differential equations." Devoid of any kinematical or mechanical property, this ether nonetheless contributes to determining the events of mechanics and electromagnetism.[83]

IV. CONCLUSIONS

It is doubtful whether the current attempt by a few to establish prior rights for Poincaré constitutes a real issue as far as Poincaré himself was concerned. The importance of his ideas on the principle of relativity and on the measures of space and time is well known. The mathematician Emile Borel, one of the founders of the modern theory of probability, stressed in the preface to a 1921 French edition of Einstein's book on a popular exposition of relativity that Lorentz and Poincaré had "discerned significant fragments" of the special theory.[84] They were forerunners of relativity, yet remained, in the words of Marie-Antoinette Tonnelat, "pre-relativists."[85] On the other hand, Poincaré's mathematical methods and results were undoubtedly important for further elaboration of the theory,[33,86] in particular by Hermann Minkowski.[87]

Poincaré was also a forerunner in the field of dynamical systems. Seventy years before the recent interest in deterministic chaos, he discovered that certain mechanical Hamiltonian systems can display chaotic behavior.[88] For this reason alone he is assured of a place in physics comparable to that to which his work in pure mathematics entitles him.

The young Einstein of 1905 was, for his part, fully aware of the need to reformulate entire areas of physics and prepared to take up the challenge. For him, the universe had to be "comprehensible." The fundamental questions, which carry the imprint of his personal approach to problems, and his results to which they led him in 1905, constitute a coherent whole. The creation of special relativity resulted from an exceptional set of circumstances, to which a physicist of exceptional stature was able to give shape. It entailed overturning our conception of the universe. The creation by Einstein of the general theory of relativity led to a new upheaval.

The method used to support the alleged prior rights consists of exaggerating the results obtained by Poincaré, results from which it *would have been possible* to infer special relativity. To do so, however, would have required doing what Einstein did—recognizing the physical nature of the connection that the principle of relativity brings about between space and time, and establishing this connection as a general law for all natural phenomena. Disregarding these necessary steps, which constitute the essence of relativity, makes it possible for the discovery of special relativity to be ascribed, as it were, *virtually* to Poincaré or to Lorentz and Poincaré.

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[49] Reference 28, p. 51.
[50] Reference 33, p. 5.
[51] M.-A. Tonnelat, *Histoire du Principe de Relativité* (Flammarion, Paris, 1971), pp. 109–110.
[52] H. Poincaré, "La dynamique de l'électron," Revue Générale des Sciences Pures et Appliquées **19**, 386–402 (1908), p. 393.
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[54] Poincaré never retracted this theory, as can be seen from the lecture "L'espace et le temps" that he gave at the University of London on May 4, 1912, which was very likely the last time he expressed his position on the matter. Reproduced in *Dernières pensées* (Flammarion, Paris, 1913); English translation: *Mathematics and Science: Last Essays* (Dover, New York, 1963).
[55] Reference 5, pp. 167–168.
[56] Reference 3, p. 48.
[57] Since then, various derivations of the Lorentz transformations besides that of Einstein have been proposed. Interesting though this question may be, it does not come within the scope of this article. See A. R. Lee and T. M. Kalotas, "Lorentz transformations from the first postulate," Am. J. Phys. **43**, 434–437 (1975); J. M. Lévy-Leblond, "One more derivation of the Lorentz transformation," *ibid.* **44**, 271–277 (1976).
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[68] Reference 5, p. 131.
[69] Reference 1, pp. 52–53.
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[86] Reference 36, p. 74.
[87] H. Minkowski, "Raum und Zeit," Phys. Z. **20**, 104–111 (1909).
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FOR GOOD OR BAD

"When nature's ways are understood, applications follow that can be used for good or bad, for peace or war. Consider the fusion of hydrogen. Einstein's relativity theory, basic physics at its best, showed how nuclear fusion could produce vast amounts of energy. Applications were soon understood. On one hand, for example, it was understood that the fusion of hydrogen occurs in the Sun and its energy nurtures life on planet Earth. On the other hand, the fusion of hydrogen can occur in a bomb and its energy can inflict devastating destruction."

John S. Rigden, *Hydrogen: The Essential Element* (Cambridge University Press, Cambridge, Massachusetts, 2005), pp. 3–4.