Henri Poincaré's St. Louis lecture, and theoretical physics on the eve of the theory of relativity

I. Yu. Kobzarev

Moscow Institute of Theoretical and Experimental Physics

Usp. Fiz. Nauk **113**, 679–694 (August 1974)

INTRODUCTION

The great French mathematician Henri Poincaré made important contributions to the development of theoretical physics, and was one of the leading theoreticians of his generation. In addition to his original work, there was considerable interest in Poincaré's review papers given at congresses, conferences, and meetings of scientific societies. Many of these can be found in Poincaré's books such as "Science and Hypothesis," "The Value of Science," "Science and Method," and "Last Essays"1). These books were widely known at the beginning of this century. Poincaré's multivolume work "Course of Mathematical Physics," which was based on the lectures given by him in the Department of Mathematical Physics in which he held the chair between 1886 and 1896, was famous throughout Europe.

Poincaré's St. Louis lecture was given by him less than a year before the appearance, in the famous Volume 17 of "Annalen der Physik," of the three papers by Einstein2) which contained the theory of relativity, the theory of Brownian motion, and the theory of light quanta. It gives a sketch of the situation in theoretical physics on the eve of the appearance of Einstein's papers, as seen by one of the most penetrating minds of the generation preceding Einstein's.

THEORETICAL PHYSICS AT THE END OF THE 19TH CENTURY

Poincaré's St. Louis lecture was given four years after the pioneering work of Max Planck on the theory of blackbody radiation, which began a revolution in theoretical physics and opened the new era in its history which was the subject of Poincaré's lecture. The main achievement of this period was the development of the atomic theory which, as suggested by the program in Poincaré's lecture, provided a description of "the great diversity of phenomena surrounding us, the whole world of hues and sounds". However, contrary to Poincaré's program, this description was based not on Newtonian mechanics, but on the new quantum mechanics.

The historical process does not, however, obey the rules of formal logic; the new period began well before the end of the old. In 1904, Poincaré and his contemporaries were largely concerned with problems which properly belonged to the pre-quantum epoch3), namely, the problems of the ether and of the statistical interpretation of thermodynamics. Most of his St. Louis lecture was in fact devoted to these topics.

Although the historical classification of such events is to some extent arbitrary, the 1905 Einstein papers signalled, more than any other event, the end of the period in the development of theoretical physics which we now refer to as classical. It is interesting to review the leading events at the end of this period, which occurred during Poincaré's lifetime.

Henri Poincaré (1854–1912) belongs to the same generation of physicists as H. Hertz (1857–1894), J. Larmor (1857–1942), P. N. Lebedev (1866–1912), H. A. Lorentz (1853–1928), A. A. Michelson (1852–1931), M. Planck (1858–1947), and J. J. Thomson (1856–1940). The range of theoretical problems which was the concern of this generation was largely prescribed by the work of Clerk Maxwell (1831–1879) who developed the theory of the electromagnetic field, and who, together with L. Boltzmann (1844–1906) and J. W. Gibbs (1839–1903), laid the foundations of statistical physics. It is therefore no accident that Maxwell's name is frequently mentioned in the St. Louis lecture.

It is now clear that several largely independent processes were taking place in theoretical physics during Poincaré's working life. This period witnessed the transition from classical thermodynamics to statistical physics in which the second law of thermodynamics, i.e., the principle of nondecrease of enthropy, was transformed from an absolute to a probabilistic statement. The statistical nature of the second law had been clear to Boltzmann and Gibbs, but it is obvious from the St. Louis lecture that this point of view was not generally accepted in 1904. This was a period of transition from the Newtonian mechanics of systems of material points with a finite number of degrees of freedom, action at a distance, and Galilean invariance, to the theory of the classical electromagnetic field with an infinite number of degrees of freedom4), contact interactions, and Lorentz invariance. Finally, the work of Max Planck and Albert Einstein began the transition to the new quantum mechanics. All this, together with the new experimental discoveries (of the electron, x-rays, and radioactivity), led to the revolution in physics which began during Poincaré's lifetime.

From the modern point of view, the first two transitions no longer seem to be particularly revolutionary. The idea of statistical physics can be traced back to at least the time of Daniel Bernoulli and M. V. Lomonosov. Einstein's theory of relativity is in a sense contained in Maxwell's equations, and the very structure of classical field theory is very close to classical mechanics.

For Poincaré himself this was not, of course, the case. From his point of view, classical physics was based on Newtonian mechanics, and its method was the causal description of physical phenomena by differential equations. Both the rejection of Newtonian mechanics (which is, in point of fact, implicit in Maxwell equations) and the explicit introduction of probabilistic descriptions into statistical mechanics were, in Poincaré's view, inconsistent with the principles of classical physics and were manifestations of a crisis. For example, his review of the statistical interpretation of Brownian motion ends with the conclusion: "we thus feel that one of our principles is in danger" (see [5], p. 668).

In 1904 it was not at all clear that theoretical physics was facing several different and largely independent problems and that, for example, the problem of the principle of relativity was not directly related to the nonclassical character of atomic spectra. Characteristic-

Copyright © 1975 American Institute of Physics

ally, Poincaré expressed the hope in the St. Louis lecture that the development of a dynamics of electrons which would be capable of explaining the unusual laws governing atomic spectra would also lead to the solution of the problems associated with the above principles, i.e., the principle of relativity, the conservation laws, and the second law of thermodynamics. In general, the entire picture appeared to Poincaré in a completely different light than it does to us, because he considered that Maxwell's theory was the phenomenological theory of the ether which could be described by Newtonian mechanics.

This is why Poincaré divided the history of classical physics into two periods, namely, the period of atomic models based on Newtonian mechanics, and the period of phenomenological theories which were also based on Newtonian mechanics but did not explicitly consider atomic models. The two main achievements of the second half of the 19th century, namely, classical thermodynamics and the electrodynamics of Maxwell, were classified by Poincaré as belonging to such theories.

It is important to note, however, that the history of physics sketched out at the beginning of the St. Louis lecture cannot, of course, be taken literally. It was merely a projection of the situation at the beginning of this century into the immediate past. If then the existence of a "crisis in physics" was considered as generally accepted, the first crisis mentioned by Poincaré could hardly be regarded as generally recognized.

The feeling that physics was in a crisis at the beginning of the century was connected with the fact that, for a very long time, it was believed that the Newtonian mechanics of central forces was the final and permanently established foundation of physics. Eventually it became clear, however, that Newtonian mechanics had only a restricted range of validity; the classical foundation was thus destroyed, and with it the illusion that a final theory could ever be found.

The change turned out to be irreversible. Although specific problems facing physics were successfully solved, there were no further theories which could pretend to any degree of finality.

Poincaré's attitude to the revolution in theoretical physics, which could be foreseen and had already begun, was not entirely unambiguous. Whilst Einstein came to the conclusion that "neither mechanics nor thermodynamics can pretend to be completely accurate, with the exception of certain limiting cases" (see [6], Vol. IV, p. 277) Poincaré was far from accepting unconditionally the necessity for this revolution, although he could see that it might become unavoidable.

In his St. Louis lecture he persistently returns to a discussion of the possibility of "retaining the principles" (see [5], pp. 673 and 676) and ends by reminding his listeners that "it has not been shown that these principles will not emerge victorious and unaltered from the battle."

Poincaré's caution may have been founded on physical intuition which suggested that principles based on an enormous volume of data could not become wholly inapplicable to new areas of experiment; his premonition was largely justified, but the principles did in fact change their form and content, and could hardly be regarded as unaltered.[5)]

It is possible that the desire to preserve the foundations of physics was one of the reasons which led Poincaré to state that the fundamental principles were in reality statements which could not, in general, be falsified by experiment (see [1], p. 182 and [5], p. 676), although he did not maintain this viewpoint consistently.[6)]

THE PROBLEM OF BROWNIAN MOTION

Poincaré began his discussion of the "crisis of principles" with the problem of Brownian motion (see [5], p. 666). The explanation of this phenomenon demanded the use of statistical ideas outside the framework of classical thermodynamics which was based on two laws, namely, the law of conservation of energy and the law of nondecreasing entropy (or, in Poincaré's terminology, the principles of Mayer and of Carnot). It is well known that classical thermodynamics developed in close interaction with the kinetic theory of gases, and also with the old ideas of the caloric theory, which is not explicitly mentioned by Poincaré in his simplified description. In its final form, thermodynamics has become a phenomenological theory based on the first and second laws, and does not explicitly involve atomic models, in accordance with Poincaré's classification.

At the same time, it was virtually unnoticed that there was a contradiction between the reversibility of the equations of mechanics and the second law of thermodynamics as discussed by Poincaré. This contradiction was clearly recognized only after the discussion following Boltzmann's statistical interpretation of entropy. In addition to the simple reversibility argument, the regression theorem discovered by Poincaré played an important role in this discussion. In the course of the discussion, Boltzmann gave the probabilistic interpretation of the second law, and found the relationship between the probability of state and entropy. However, it is clear, for example from the Poincaré lecture, that Boltzmann's point of view, summarized in his lecture at the St. Louis Congress (see [7], p. 163), was not generally accepted. In particular, although the fluctuational explanation of Brownian motion given in Poincaré's lecture had long been known, had been discussed by several authors, including Ramsey in 1876, and was mentioned by Gouy in 1888 (see [8], pp. 98–99), Poincaré himself considered the problem of Brownian motion as unresolved. In actual fact, the difficulty was the absence of a quantitative theory.

INTERPRETATION OF MAXWELL'S EQUATIONS

The statistical interpretation of the second law was found relatively rapidly, although it was not generally accepted for a long time. The road toward a complete elucidation of the significance of Maxwell's equations was much longer and much more difficult. Electrodynamics can be developed in a rigorous fashion only on the basis of the Einstein relativity principle, and the significance of Maxwell's equations became completely clear only after the development of the theory of relativity.

This required a review of the fundamental ideas of classical physics on space and time, and a rejection of the idea of Newtonian mechanics as the foundation of physics.

This was why, for Poincaré, the crisis in physics was connected, above all, with the modification of the principles of physics (in fact, the principles of classical mechanics) which was required for a rigorous interpretation of Maxwell's equations, and the associated problems became inseparable from the problem of relativity.

Initially, the significance and content of the Maxwell theory were completely obscure. The eminent theoretician of the second half of the 19th century, Tait, wrote in 1879 in his obituary of Maxwell that, since the velocity of light calculated from electromagnetic constants was the same as the measured velocity, "there is very little doubt now that Maxwell's theory of electrical phenomena rests on an equally firm foundation as the wave theory of light. However, the creator of the theory, who spent all his life working on it, did in fact leave it in its infancy. The efforts of a whole generation of mathematicians will probably be required in order to achieve its full development." Tait's prediction turned out to be somewhat too optimistic: two generations were required, namely, the generation of Lorentz and that of Einstein.7)

Maxwell gave his final formulation of electrodynamics in 1864 and an account of it was published by him later in his "Treatise on Electricity and Magnetism" (1873). The Maxwell equations were written in terms of two pairs of fields, namely, **E**, **D** and **B**, **H**, the current equation $J = \sigma E$, and the potentials **A**, φ, so that the system of equations had a more complicated form than is used nowadays. Maxwell was probably disinclined to look upon current as a motion of charges; for him this interpretation was connected with the idea of electrical fluids which his theory was intended to replace.8)

For a long time after the appearance of the Maxwell theory attempts were made, and they were begun by Maxwell himself, to explain his equations in terms of mechanical models of the ether, the possibility and necessity of which was initially undoubted. Poincaré considered that the Maxwell theory had to be looked upon as a phenomenological description of the ether. It was thought to have been analogous to thermodynamics which gave a phenomenological description of a set of atoms. Like many of his contemporaries, Poincaré suggested that Maxwell's equations were in fact the Lagrange equations describing the mechanics of the ether in terms of generalized coordinates (charges, currents, and field strengths). It was supposed that this was a Newtonian mechanics. The justification for this was seen in the electrodynamics of the principle of least action which was known to Maxwell for the quasistationary case. The action for the electrodynamic field in vacuum was known at the beginning of this century; it is given, for example, in Larmor's book (see[13], pp. 82–104).

Starting with the assumption that any system described by Newtonian mechanics satisfies the principle of least action, Poincaré concluded that, once the principle of least action could be established for the field, a Newtonian model should also exist (see[1], pp. 236–244), but he appeared to regard attempts to develop specific models with some skepticism.

The modern theory of the electromagnetic field in vacuum was largely developed by Lorentz who, instead of Maxwell's electrodynamics, considered the electrodynamics of two fields, namely, **E** and **H**, interacting with charges. Lorentz, however, considered, as before, that the carrier of the field was the ether, and it is interesting to note that he looked upon his own electrodynamics as a partial return to pre-Maxwell ideas, since his theory included the point charge as one of its main elements.9)

From the formal point of view, the Lorentz theory can be reduced to the equations for the fields and the formula for the force on a charge, namely, $\mathbf{F} = e\mathbf{E} + (e/c)(\mathbf{v}\times\mathbf{H})$. The electromagnetic part of the Lorentz equations was therefore identical with the modern version of the system. All that remained was to find a relativistic expression for the electron momentum, and to dispose of the ether.

SEARCHES FOR THE ETHER

The key to the solution of the problem turned out to be the question of absolute motion, i.e., motion relative to the ether. Maxwell had no doubt as to the reality of the ether, and the demonstration of its existence was one of the main problems in physics. Ideas based on Newtonian mechanics suggested a direct and immediate method for the detection of the ether. What was required was the detection of the change in the velocity of light relative to the Earth due to the motion of the Earth through the ether. Maxwell discussed this type of experiment in his paper "The Ether," which he wrote shortly before his death, and in greater detail in his letter to the American astronomer Todd, which was published posthumously in 1879.10) In both publications Maxwell discussed the possibility of detection of the motion of the solar system relative to the ether through observations of the satellites of Jupiter. Within the framework of Newtonian mechanics, it was expected that this would give rise to an effect of the order of v/c where v is the velocity of the solar system relative to the ether. Maxwell also noted that terrestrial methods of measurement of the velocity of light always require a closed trajectory, i.e., an effect of the order of $v^2/c^2 \sim 10^{-8}$, which he regarded as undetectable.

However, as early as 1881, Michelson, who at the time was working at the Helmholtz laboratory in Berlin, attempted to detect the quadratic effect discussed by Maxwell by an interferometric method. This experiment gave a negative result.11)

At the time when the experiment was suggested, the problem of the ether in optics had already had a long history, the beginnings of which can be traced back to Huygens. Among the effects which, it was thought, were directly connected with motion relative to the ether were the well-known aberration phenomena, the Doppler effect, and the so-called partial drag of light by moving media.12) We recall that the partial drag is described by the Fizeau-Fresnel formula

$$c_1' = c_1 + v\left(1 - \frac{1}{n^2}\right),$$

where n is the refractive index of the medium (say, water), $c_1 = c/n$ is the velocity of light in the medium at rest, v is the velocity of the medium relative to the ether, and c_1' is the velocity of light relative to the ether. From the modern point of view, the velocity relative to the ether must be interpreted simply as the velocity relative to the laboratory set of coordinates, and the Fizeau-Fresnel formula itself is an obvious consequence of the relativistic law of composition of velocities. At the time, however, this formula necessitated the introduction of the ether and, consequently, the rejection of the idea that all inertial systems were equivalent.

Lorentz first approached the problem of the optics of moving media in a paper published in 1886.13) He used the Fizeau-Fresnel formula to show that, to within terms of the order of v/c, effects associated with the motion of the medium cannot be seen in optical phenomena and, therefore, to this accuracy, motion relative to the ether is undetectable.[14] This explained the negative result of many of the earlier attempts to detect motion relative to the ether, but not, of course, the result of the Michelson experiment in which an effect of the order of v^2/c^2 was investigated. A detailed analysis of this experiment led, however, to the discovery by Lorentz that Michelson overestimated the expected effect by a factor of 2 because he did not take into account the time taken by light to propagate in the direction perpendicular to the velocity of the apparatus relative to the ether. When this error was corrected, the expected effect was found to be of the order of the experimental uncertainty, and the problem became less serious.

However, in the following year (1887), Michelson repeated his experiment in collaboration with Morley in the USA, and obtained an upper limit for the effect which was of the order of 1/20—1/40 of the expected value. As in 1881, Michelson himself considered that his result was a confirmation of the Stokes theory, which was put forward at a time, according to which only a partial drag of the ether took place in the neighborhood of the Earth. This explanation turned out to be unacceptable; Lorentz showed that the Stokes theory was mathematically inconsistent.[15]

THE LORENTZ-FITZGERALD CONTRACTION

In 1892 Lorentz published a short paper[16] in which he wrote: "the puzzle of this experiment (the Michelson experiment) has disturbed me for a long time until I saw a method of making it consistent with the Fresnel theory." The method used by Lorentz in this paper was to introduce the hypothesis of contraction of bodies moving relative to the ether. This contraction subsequently received the name of the Lorentz-Fitzgerald contraction.

Lorentz mentioned in his paper that this contraction could be deduced from electrodynamics. He used it to compare forces acting on a system of charges B moving relative to the ether with velocity v, and the forces in a frame C which was at rest relative to the ether and whose longitudinal dimensions were increased by the factor $1 + (v^2/2c^2)$. The longitudinal components of the forces in frames B and C were then equal, but the transverse components in B were smaller than in C by the factor $1 - (v^2/2c^2)$.

If we suppose that molecular forces are also transformed in accordance with the same law, and that in the body at rest these forces are balanced, then they will also be balanced in the moving body after the longitudinal contraction has taken place. The contraction introduced by Lorentz, and previously considered by Fitzgerald,[17] had thus received a dynamic explanation[18]. In fact, this early paper contained the basic idea which was taken to its ultimate conclusion by Lorentz in 1904 and by Poincaré in 1905; the impossibility of detecting motion relative to the ether was established as a consequence of dynamic compensating effects which ensued from the equations of the electrodynamics of Lorentz.

In his 1892 paper, Lorentz confined his attention to the static case. Generalization to the case of internal molecular motions required the use of relativistic mechanics and gave rise to considerable difficulties. The series of important steps towards a solution of this problem made by Lorentz in the 1890s was summarized by him in his book "An Attempt to Construct the Electrodynamics of Moving Media" which was widely known at the time (see [14], p. 1). In this book, Lorentz analyzed the correspondence between motions in frames which were moving and were at rest relative to the ether. He used the local time t′ in the "nonrelativistic" form[19]

$$t' = t - \frac{v}{c^2}(x - vt)$$

and employed it to show that, in his electrodynamics, motion relative to the ether was undetectable to the order of v/c.[20] He also showed that the Fizeau-Fresnel formula was valid in his electrodynamics. None of this provided an explanation of the Michelson experiment, and the discussion of the experiment given in this book was the same as that given in the 1892 paper.

POINCARE'S POSITION IN 1895-1900

Poincaré became interested in the electrodynamics of moving bodies after Lorentz. In 1895 he published a series of papers on the electrodynamics of moving bodies, which were largely reviews of previous work.[21]

In his third paper Poincaré summarizes the conditions which, in his view, had to be satisfied by the electrodynamics of moving bodies:

1) the theory must explain the Fizeau experiment, i.e., the fact that light (i.e., transverse electromagnetic waves) is dragged by moving media but only partially;

2) the theory must be consistent with the law of conservation of electricity and magnetism;

3) the theory must be consistent with the principle of equality of action and reaction.

By way of an explanation, we note that under (2) we must understand the conservation of charge and the condition div B = 0, and under (3) we must understand the requirement of conservation of momentum for gravitating matter or, in present-day language as applied to particles, Poincaré considered that the ether should not transport momentum.

At the end of his paper Poincaré noted the failure of experiments designed to detect motion relative to the ether and, referring to the Michelson experiment, expressed his belief that this motion was undetectable in principle.

Poincaré's brilliant guess appeared to be inconsistent with the existence of the ether, but one of the fundamental features of the electrodynamics of Lorentz was the nonconservation of momentum for gravitating matter, and this was thought to show that momentum should be transferable to the ether.

It is therefore not accidental that Poincaré thought that in any future theory the momentum of gravitating matter will be conserved [requirement (3)] and that, by analogy with mechanics, any theory in which absolute motion is undetectable will also be subject to condition (3), i.e., the equality of action and reaction for gravitating matter.

Despite the fact that the electrodynamics of Lorentz did not satisfy this requirement, Poincaré nevertheless considered it to be the "least unsatisfactory" in comparison with other theories, and expressed the hope that further development of the theory would remove its defects, i.e., the absence of a demonstration of the impossibility of detecting motion relative to the ether to all orders in v/c, and the nonconservation of momentum for particles. He suggested that these defects were related and would be removed at the same time.

In 1900 Poincaré read a paper to an international meeting of physicists in Paris which appeared as chapters 9 and 10 in his book "Science and Hypothesis." Here Poincaré again notes (see[23], pp. 186–189) the two defects of the electrodynamics of Lorentz, namely, the nonconservation of momentum and the absence of a rigorous explanation of the failure of attempts to detect motion relative to the ether, and again suggests that this motion is undetectable in principle.

There are indications in Poincaré's paper which could be interpreted as doubts in the existence of the ether, but these doubts can always be also interpreted as doubts in the electrodynamics of Lorentz. In an electrodynamics in which electromagnetic radiation can transport momentum, ether seemed to him to be essential.

In the same book (Chapter 6) Poincaré emphasized that the simultaneity of events occurring at different points in space required a definition and was not unambiguously obvious.22)

THE PRINCIPLE OF RELATIVITY IN POINCARÉ'S LECTURE AND THE CONCLUDING WORK BY LORENTZ AND POINCARÉ

The discussion of the problem of the principle of relativity in Poincaré's 1904 lecture was largely based on two publications, namely, his 1900 paper (see[25], p. 464) and the celebrated paper by Lorentz published in 1904.23)

Poincaré's 1900 paper was devoted to a detailed analysis of the laws of conservation in the electrodynamics of Lorentz and Hertz.24) He showed that, in the Lorentz electrodynamics, momentum will be conserved if the ether is given a momentum density which, in modern motation, is equal to $(1/4\pi c)(\mathbf{E}\times\mathbf{H})$. Following his own general ideas, Poincaré identified this momentum with the momentum of the "atoms of the ether." The conclusion that the assumptions which must be introduced to describe motions in the ether are unsatisfactory (see[5], p. 671) derives from this interpretation. In fact, when the charges in the radiator are doubled, the momentum carried away is increased by a factor of 4 and, consequently, the velocity of the atoms of the ether should also increase by a factor of 4. Poincaré considered (probably because forces should always be proportional to charges) that it was more natural to expect that the velocity would increase by a factor of 2.

This article also discusses the interpretation of the local time $t' = t - (v/c)(x - ct)$ introduced by Lorentz as the time which appears as the result of synchronization by light in a moving reference frame. Poincaré, however, considered that an observer moving relative to the ether would not notice his own motion precisely because the time used by him would be different from the true time (see[5], p. 671).

In the 1904 paper by Lorentz we find the decisive step toward a demonstration that the Lorentz electrodynamics was consistent with the undetectability of motion relative to the ether. To understand these papers, and the 1905 papers by Poincaré in which the proof was taken to its ultimate conclusion, it is important to recall that both in these papers and in the previous papers by Lorentz, no use was made of the coordinates and time measured by clocks and scales in the moving coordinate frame. As we have seen, the question of the time measured in a moving reference frame had been discussed by Poincaré but, nevertheless, in the 1905 papers he followed the analysis given by Lorentz and did not discuss this interpretation.

In the 1904 paper, Lorentz used the transformation for the time and the coordinates which now bears his name,25) and the corresponding transformation for the electromagnetic fields. However, as in his previous papers, right back to 1892, the primed and the unprimed variables (x', y', z', t', $\mathbf{E}'$, $\mathbf{H}'$, etc., and x, y, z, t, $\mathbf{E}$, $\mathbf{H}$, etc.) related by these transformations described two different systems of bodies Σ' and Σ in the <u>same</u> set of coordinates at rest relative to the ether. The system of bodies Σ' is at rest, and the system Σ moves, relative to the ether. The Lorentz transformations transform a particular solution of the Maxwell-Lorentz equations describing the moving system Σ into another solution which describes the resting system Σ'. In this transformation, there is no change in the internal relationships in the system of bodies. Thus if $\mathbf{E}'$, $\mathbf{H}'$ are both zero at the point x', y', z', t', then $\mathbf{E}$, $\mathbf{H}$ will vanish at the point x, y, z, t.26) This explained, for example, the absence of a shift in the fringe system in the Michelson interferometer, and the undectability of motion relative to the ether.

In fact, Lorentz divided the transformations into two stages. He first considered the solution corresponding to the system Σ which was moving relative to the ether. He then followed tradition and used the Galilean transformation to a coordinate frame moving together with Σ. In terms of the new coordinates, the equations had a different form. Lorentz then looked for substitutions which would bring them back to the original form. The new fields $\mathbf{E}'$ and $\mathbf{H}'$ which had to be introduced for this purpose, and were looked upon as functions of x', y', z', t', were again a solution of the Maxwell-Lorentz equations. From Lorentz's point of view, this solution described the system Σ'' which was at rest relative to the ether.

The method used by Lorentz is in itself completely possible. From the modern point of view, all that is required is to perform the analysis in a certain arbitrarily chosen inertial frame of reference. This then has to be followed by an analysis of the result of measurements performed in a reference frame moving together with the body Σ. This would show that it was precisely because of the conservation of internal relationships that the primed variables were also the coordinates, times, and fields measured in the moving frame of reference,27) whilst the contraction of length and slowing down of clocks,28) which are produced by the transformation, are relative and not absolute.

However, neither Lorentz nor Poincaré succeeded in making this step in their subsequent papers and, for them, the contraction of length, which followed from the Lorentz transformation, was an absolute effect. In the words of the paper: "One of the diameters of the Earth should contract as a result of the motion of the planet by the fraction 1/200 000 000" in the direction of motion.

Lorentz's development, taken together with the hypothesis that all forces and masses transform by the same law as the electromagnetic29) forces, was in principle complete because it explained the undectability of motion relative to the ether. In actual fact, Lorentz did not give the complete proof in 1904. He could not find the correct transformations for the current and charge.

The last fact, and also the fact that Lorentz's method did not exhibit right from the outset the universality of relativistic relationships, had the consequence that in his analysis of Trouton's experiment, in which an attempt was made to detect absolute motion, Lorentz did not conclude that the effect should be absent, but merely that it was undectable under the actual experimental conditions.[30)]

THE 1905 POINCARÉ PAPERS

The gap in Lorentz's paper was filled by Poincaré in two papers published in 1905.[31)] The first of these appeared on June 5th and contained a brief summary of the results, and the second provided a detailed account. The first paper gives the Lorentz transformations for the coordinates and time in a form practically identical with their modern form, and also the correct transformations for the fields, the charge and current densities, and the Lorentz force. Poincaré showed that the Lorentz transformations form a group under which the equations of the Lorentz electrodynamics are invariant. And he concluded that, in accordance with Lorentz's idea, the solution describing a moving set of bodies is a "deformed" representation of the solution describing the system at rest; at the same time, the transformation does not affect the internal relationships in the system.

Thus, the principle of relativity, i.e., the undectability of motion relative to the ether, was found to be satisfied subject to the condition that all the forces transformed in accordance with the same law as the electromagnetic forces.[32)] In Poincaré's words, he had an explanation of "both the undectability of absolute motion and the contraction of all bodies in the direction of motion of the Earth" (see [25], p. 491).[33)]

The Lorentz-Poincaré program (the derivation of the Lorentz group as the invariance group for the equations describing electron dynamics) could not, of course, be completed because it required knowledge of the structure of the electron, which we do not have even now. In his analysis of the dynamics of the electron, Poincaré was forced to introduce additional artificial hypotheses because the question of the structure of the electron could not be avoided either by himself or by Lorentz in their analysis of the equations of motion of the electron and in the calculation of the electromagnetic mass. As we have seen, Poincaré continued to regard the Lorentz-Fitzgerald contraction as an absolute effect, and the satisfaction of the principle of relativity as the result of compensation. In this form, the requirement of universal Lorentz invariance appeared to be artificial. The situation therefore seemed to Poincaré to be unsatisfactory, and in his concluding paper (see [29], pp. 55—56) he wrote:

"Consider an astronomer living before Copernicus and contemplating the Ptolemaic system; he would note that, for all the planets, one of two circles, the epicycle or the deferent (the main circle), is traversed in the same time. Since this could not be accidental, it would follow that some hidden connection existed between all the planets.

However, Copernicus changed only the coordinate axes, which were previously regarded as fixed, and at once removed this apparent connection; each planet describes only one circle, and the periods of revolution become independent of one another (until Kepler establishes between them the connection which was regarded as removed).

It is possible that in our case we have a somewhat similar situation; if we accept the principle of relativity, we find a common constant, namely, the velocity of light, in the law of gravitation and in the laws of electromagnetism. In precisely the same way we encounter it in all forces, whatever their origin, and this can be explained only from two points of view: either all that exists in the world is of electromagnetic origin, or this property which appears, so to speak, to be common to all physical phenomena is simply the external manifestation of something connected with our method of measurement. How have we carried out our measurements? Previously we would say: by transporting bodies regarded as solid and invariable, and bringing them up against each other; however, in the modern theory, in which we have to take into account the Lorentz contraction, this is no longer valid. According to this theory, two segments are equal, by definition, if they are traversed by light in equal times.

It may be that, if we abandon this definition, the Lorentz theory will be completely destroyed, which is what happened to the Ptolemaic system after the intervention of Copernicus. At any rate, even if this does happen it will still not prove that the efforts of Lorentz were useless because, whatever one thinks of Ptolemy, his efforts were certainly not useless for Copernicus."

THE THREE EINSTEIN PAPERS

Where Poincaré doubted and vacillated, the young Albert Einstein went forward and found new and unexpected solutions.

On June 30, 1905, the editors of "Annalen der Physik" received a paper entitled "On the electrodynamics of moving bodies." The appearance of this paper was the Copernican revolution, the possibility of which was mentioned by Poincaré.[34)]

Einstein's paper is based on an analysis of the physical content of the concepts of time and position of events measured in an arbitrary inertial reference frame.[35)]

Both Lorentz and Poincaré stopped just short of Einstein's conclusion that it follows from the undectability of absolute motion that all inertial systems are completely equivalent, that there is no privileged reference frame attached to the ether, and that the ether is itself superfluous. To make this deduction it was necessary to introduce the electromagnetic field in vacuum as a new type of physical object, and this meant a radical break with existing ideas, including those of Lorentz and Poincaré.

The equivalence of all inertial frames meant the equivalence of spacetime coordinates measured in inertial reference frames. Einstein gave a systematic description of methods used to measure time and position in an arbitrary inertial frame and, for the first time, explicitly formulated and solved the problem of the relationship between spacetime coordinates in two reference frames when the time is measured by clocks synchronized with light and the coordinates are measured by standard scales.[35)] This relationship was deduced by Einstein from two postulates, namely, the principle of relativity and the postulate that the velocity of light is independent of the motion of the source.[36)] It was only after this was done that Einstein could maintain that the laws of electrodynamics and of optics have the same form in all frames of reference, and could show that the postulate of relativity, interpreted as the requirement that the laws of nature should have the same form in all inertial frames, can in fact be satisfied.

At the same time, the requirement that the equations of physics must be invariant under relativistic transformations of the spacetime coordinates, which we now call the Lorentz transformation, became an obvious consequence and an expression of the equivalence of all inertial frames.

The revolutionary result of Einstein's paper was the conclusion that quantities such as length and time, and the concept of simultaneity, were all relative and dependent on the reference frame employed. Once this conclusion was made it became clear that the Lorentz-Fitzgerald contraction was not a "real" contraction of the body due to its motion through the ether, which was maintained by Poincaré and Lorentz, but merely a manifestation of the relativity of length, while the impossibility of detecting absolute motion was connected not with compensation of various effects due to the motion through the ether, but with the relativity of length, time, and simultaneity.[37]

In this way, Einstein developed the theory of relativity as a physical theory of spacetime based on the relative character of the relativistic effects of dilation of time and contraction of length, and the problem of the principle of relativity was resolved once and for all.[38]

Einstein's paper occupies a special place in modern physics. It was the first application of the principles of invariance in the way now commonly employed. In contrast to the work of Lorentz and Poincaré, Einstein did not consider the derivation of this invariance from known and given equations. Instead, he looked upon the principle of relativity as a basic postulate of the theory, justified by experiment. The transformations corresponding to the given invariance were determined from a minimum set of postulates, and the requirement of invariance under these postulates was used to establish connections between physical quantities. This enabled Einstein to avoid difficult dynamic problems involving the structure of particles. It turned out that the basic relationships depend not on the details of the dynamics but on the general properties of the Lorentz group. The method turned out to be extremely fruitful.

In particular, the tangled problem of the connection between mass and energy was simply resolved by Einstein. He soon showed that $E = mc^2$, and this led him to the conclusion that radioactive materials may exhibit mass defects.

The other problem discussed in Poincaré's paper was solved by Einstein in his paper on the theory of Brownian motion where he gave a quantitative theory of this effect which was amenable to direct experimental verification. This paper, and the analogous work by Smoluchowski, amounted to a physical completion of the development of statistical physics, and revealed a way toward a direct experimental demonstration of the probabilistic nature of the second law of thermodynamics. A direct verification of the theory was made soon after by Perrin.

In this way, the crisis defined by Poincaré was rapidly resolved: classical mechanics was replaced by the relativistic version of the electrodynamics of Maxwell and Lorentz, and thermodynamics was replaced by statistical physics.

When this was done, and the foundations of classical physics became clearer and simplified, physics had to face a much deeper revolution. Poincaré's striking insight did not fail him here either: studies of the properties of spectra did in fact yield "the greatest surprises".

In the same year, 1905, Einstein published a paper entitled "On a heuristic point of view in relation to the generation and transformation of light" in which he extended Planck's ideas and took the next step into the "third period" in mathematical physics in which the laws of nature did in fact assume the character of statistical laws. Another twenty years had to elapse, however, before a consistent theory capable of explaining the nonclassical properties of radiation spectra mentioned by Poincaré was developed.

Although in their content the Einstein papers on the special theory of relativity and his subsequent papers on the general theory of relativity belong to classical physics as we now understand it, in their spirit and style these papers belong to the new period in the history of physics.

Einstein showed that commonsense ideas, which seem immediately obvious, are not applicable to the new phenomena. He also demonstrated that mathematical theories which seem abstract and far removed from physics can in fact be used to describe new and unusual relationships. Having revolutionized the thinking of physicists, the theory of relativity prepared them for the still more radical departure from commonsense ideas, which was required for the development of quantum mechanics.

In conclusion I should like to thank V. B. Berestetskiĭ, V. N. Gribov, and L. B. Okun' for numerous stimulating discussions, Ya. A. Smorodinskiĭ for a series of interesting communications and for pointing out to us Holton's paper[18], and V. P. Murat for assistance with the translated text of Poincare's lecture.

---

[1] Originally published in 1902, 1904, 1908, and 1913 ("Last Essays" was published posthumously). These books were translated into the major European languages, including Russian. [1-4]

[2] Russian translations in [6] Vol. I, p. 7 and Vol. II, pp. 92 and 108.

[3] The papers by Max Planck were not mentioned by Poincaré.

[4] The mathematical formalism of the theory, i.e., partial differential equations, was already being used in the mechanics of continuous media, but there it was merely a method for phenomenological description.

[5] Poincaré considered this possibility and emphasized that, if it were true, previously established relationships should be contained in the new ones as limiting cases, and should thus retain their significance (see [5], p. 677).

[7] The history of the initial period in the development of the theory of the electromagnetic field after the publication of Maxwell's papers is discussed in [10,11].

[8] In his discussion of the problem of electrolysis, for example, Maxwell wrote: "it is extremely improbable however that when we come to understand the true nature of electrolysis we shall retain in any form the theory of molecular charges [11,12].

[9] In 1895 Lorentz wrote: "To some extent, the assumptions which I have introduced constitute a return to older ideas. This does not invalidate the essence of Maxwell's ideas, but one cannot deny that the ions which I have introduced are not very different from the electrical particles used previously" ([14], p. 8).

[10] This is the paper entitled "The Ether" in Encyclopaedia Britannica

(see [15], p. 763); the letter to Todd was published in "Nature" [16].

[11] For information on these and subsequent experiments by Michelson see [17-14].

[12] The early history of the optics of moving media and of the problem of the ether is given in [20-22].

[13] "On the effect of the motion of the Earth on optical phenomena"; the electromagnetic theory of light is not yet used in this paper (see [23], p. 153).

[14] The proof refers to situations where only the space path lengths are determined. The experiment suggested by Maxwell in his letter to Todd does not belong to this category. In modern language, this proposes that the Jupiter satellites and the clocks belonging to the observer on the Earth are clocks synchronized in "Newtonian" time and moving in space.

[15] Lorentz frequently returned, aright up to 1899 (see [23], pp. 224, 237, 245), to the possibility of an explanation of the Michelson experiment in terms of a modification of Stokes' theory. Michelson attempted to verify Stokes' theory in an independent experiment in 1897.

[16] "On the relative motion of the Earth and the Ether" (see [23], p. 219).

[17] The Fitzgerald hypothesis was published in "Science" in 1889. Lorentz apparently learnt about it in 1894 from a paper by Lodge (see, [18] pp. 179-182).

[18] The logic of the Lorentz analysis is still partly obscure. For example, it is stated in [24] (p. 168) that Lorentz never carried out the calculation explaining the contraction.

[19] As always, Lorentz considered two processes: one occuring in the resting system and the other in the moving system of particles. The time t is the time of the event in the moving system of particles (bodies) and t′ is the time of the corresponding event in the resting system. In both cases the time t′ and t are measured in terms of the universal "Newtonian" time.

[20] That was the best that Lorentz could do at the time because he used the Newtonian expression for the momentum of the electron.

[21] These papers were published in the journal "L'Eclairage Electrique" and reprinted in the collected works of Poincaré ([25], pp. 369-426); see also the discussion in [26].

[22] See [1] p. 103. Poincaré discussed this earlier in [27].

[23] "Electromagnetic phenomena in a system moving with a velocity less than the velocity of light". Russian translation in [28] p. 28 and [29] p. 16.

[24] The electrodynamics of Hertz satisfied Gaililean invariance. In Poincaré's interpretation, it conserved the momentum of "gravitating matter". At the same time, the theory did not allow the limiting transition to empty space, and led to complete dragging of light by a moving medium.

[25] A similar type of transformation was used by Lorentz in 1899 (see [14], p. 139). The correct form for the transformations was found by Larmor in 1900 (see [13], p. 173). A very similar transformation was employed by Voigt. [30]

[26] The actual notation and analysis used by Lorentz were more complicated. In particular, he used primed quantities as auxiliary variables for the description of the system Σ (without ascribing to them any physical significance), and in the description of Σ' he occasionally transforms to unprimed quantities numerically equal to the primed ones.

[27] Poincaré's lecture (see [5], p. 172) gives the impression that this interpretation was known to him. However, in reality, this was merely a guess which remained undeveloped. This is clear from the fact that, even in 1908, when Poincaré gave an account of the question of the invariance of the velocity of light, he introduced a number of erroneous statements (see [25], p.575). The reciprocity of the Lorentz transformations was discussed by Poincaré in [4] (p. 30), but only after the publication of Einstein's paper.

[28] It is emphasized in [31] that neither Lorentz nor Poincaré ever discussed the slowing down of clocks, which is implicit in the Lorentz transformations. A special case of this was discussed by Larmor (see [13], p. 174). A complete analysis of the meaning of the transformations was given only by Einstein. A phenomenon now known as the "twin paradox" is discussed in [6] (p. 19).

[29] One of the more important achievements of Lorentz's work was that he introduced (without justification) the hypothesis of relativistic contraction for the electron and, assuming that its mass was purely electromagnetic, obtained an expression for the momentum and mass with the correct transformation properties.

[30] Trouton tried to detect the impulse connected with the loss of momentum associated with the electromagnetic field which was thought to occur during the discharge of a capacitor moving relative to the ether. To explain the negative result of this experiment one has to know either the universal formula $E = mc^2$ or to assume that, once the invariance of the equations was proved, the effect looked for could not be detected.

[31] The first of these [32] appeared in "Comptus Rendus" of June 5, 1905. The second paper was sent on July 23, 1905 to the journal "Rendiconti del Circalo Matematico di Palermo." The papers were reprinted in [29] (pp. 489 and 494) (Russian translations in [29], pp. 113-129).

[32] In this connection, Poincaré made an attempt to write down the law of gravitation in Lorentz-invariant form by introducing retarded potentials (see [29], pp. 113-129).

[33] The translation given in [34] does not reproduce the true meaning of this phrase.

[34] Einstein's theory of relativity given in this paper has subsequently been frequently compared with the theory of Copernicus. Poincaré himself never indicated his attitude to Einstein's theory. He never acknowledged the theory of relativity. Nevertheless in a posthumously published book by Poincaré [4] (p. 21 ff) the problem of the principle of relativity is discussed with, in our view, an indication that Einstein's paper was known to Poincaré (the ether is no longer mentioned and the relative character of the various effects is discussed). However, Poincaré uses the phrase "the principle of relativity of Lorentz" by which he means the invariance of the laws of physics under the Lorentz transformation. The question as to why Poincaré (in contrast to Lorentz) never indicated in print his attitude to Einstein's paper, and to what extent Einstein was familiar with the papers by Lorentz and Poincaré at the time when he was working on his own paper, lies outside the framework of the present article. Factual evidence is very slight. It is shown, however, that Einstein was familiar with the book by Lorentz published in 1895 and with Poincaré's "Science and Hypothesis." The 1908 paper by Poincaré was probably written before Poincaré became aware of Einstein's paper (see footnote 27).

[35] This term was not used as yet in Einstein's paper.

[36] Poincaré found the relationship between the local time of Lorentz (in the v/c approximation) and synchronization by light, within the framework of the ether theory, but the idea was never developed. Published papers by Poincaré and Lorentz contained no indication of an analysis of the measurement of coordinates and this, as already noted above, resulted in a different interpretation of x′, y′, z′, t′ and did not lead to the equivalence of all inertial systems.

[37] The formulas found by Einstein are mathematically identical with the Lorentz formulas, but both Lorentz and Poincaré give them a different physical interpretation.

[38] See, for example, the description of the difference between the Lorentz point of view and the Einstein relativity principle, given by Lorentz ([28], pp. 133-134).

[39] It is sometimes suggested that the originators of the theory of relativity were Lorentz and Poincaré (see [21], Vol. II, p. 40 and Russian translations in [34]), or Larmor, Lorentz, Poincaré, and Einstein ([34], p. 303). Writers who adhere to this point of view do not take into account the basic idea of the work of Lorentz, Larmor, and Poincaré, namely, the comparison between a moving and a stationary body (relative to the ether) in the reference frame of the ether. This may be so because these papers are difficult to understand, which leads to erroneous interpretations of them. For example, Whittaker gives an account of the Einstein paper, but considers that he is giving an account of the Lorentz and Poincaré relativity theory, whilst A. A. Tyapkin considers that a key section in the Lorentz 1904 paper, namely, the transformation to the system Σ' (see [34], p. 287 ff) was a mistake.

The question as to who can be considered as the originator of the theory is largely meaningless because science is the product of the labors of many people. It is well known that the papers by Lorentz, Larmor, Poincaré, and others contain many of the ideas and results which lie at the basis of the theory of relativity. Credits are frequently somewhat arbitrary but, when they speak of the Einstein theory of relativity, physicists simply acknowledge the importance of the fundamental step made by Einstein: he was the first to understand that the principle of relativity is intimately connected with the relativity of time and length. This was a crucial moment in the long history of theory and experiment, and was an achievement which will ensure that Einstein's name will "rank equally with that of Copernicus" in the view of Herman Weil, the author of one of the better books on the theory of relativity ([36], p. 164).

---

[1] H. Poincaré, Science and Hypothesis, Dover, 1952 (Russ. Transl. T-vo tip. A. I. Mamontova, M. 1904).

[2] H. Poincaré, The Value of Science, Dover, 1952 (Russ. Transl. "Tvorcheskaya mysl'," M. 1906).

[3] H. Poincaré, Science and Method, Dover, 1952 (Russ. Transl. SPb, Izd. N.P. Karbasnikova, 1910).

[4] H. Poincaré, Last Essays, Dover, 1963 (Russ. Transl. Pg., "Nauchnoye knigoizdatel'stvo," 1923).

[5] H. Poincaré, Bull. des Sciences Math. sér. 2, 28 (pt. 1), 302 (1904).

[6] A. Einstein, Sobranie nauchnykh trudov (Collected Scientific Works), I—IV, Nauka, M. 1965—1967.

[7] L. Boltzmann, Stat'i i rechi (Articles and Speeches) Nauka, M. 1970.

[8] J. Perrin, Les Atomes, Redaction Nouvelle, 1936 (Russ. Transl. GI, M. 1924).

[9] P. G. Tait, Nature 21, 317 (1879).

[10] A. M. Bork, Science 152, 597 (1966)].

[11] I. S. Shapiro, Usp. Fiz. Nauk 108, 319 (1972) [Sov. Phys.-Uspekhi 15, 651 (1973)].

[12] J. C. Maxwell, A Treatise on Electricity and Magnetism, Vol. 1, Oxford, 1904, p. 381.

[13] J. J. Larmor, Aether and Matter, Cambridge, 1900.

[14] H. A. Lorentz, Collected Papers, Vol. 5, The Hague, Nijhoff, 1937.

[15] J. C. Maxwell, Scientific Papers, Vol. 2, Hermann, P. 1927 (reprint).

[16] J. C. Maxwell, Nature 21, 314 (1879).

[17] S. I. Vavilov, Eksperimental'nye osnovaniya teorii otnositel'nosti (Experimental Foundations of the Theory of Relativity), GIZ, M.-L. 1928.

[18] G. Holton, Isis 60, 133 (1969).

[19] Tvortsy fizicheskoĭ optiki (Creators of Physical Optics), Nauka, M. 1973.

[20] L. I. Mandel'shtam, Lektsii po optike, teorii otnositel'nosti i kvantovoĭ mekhanike (Lectures on Optics, Relativity, and Quantum Mechanics), Nauka, M. 1972.

[21] E. T. Whittaker, History of the Theories of Aether and Electricity, Harper, N.Y., 1960.

[22] U. I. Frankfurt and A. M. Frenk, Optika dvizhushchikhsya tel (Optics of Moving Bodies), Nauka, M. 1972.

[23] H. A. Lorentz, Collected Papers, Vol. 4, The Hague, Nijhoff, 1937.

[24] S. Goldberg, Am. J. Phys. 37, 982 (1969).

[25] H. Poincaré, Oeuvres, Vol. 9, Gauthier-Villard, P., 1954.

[26] S. Goldberg, Am. J. Phys., 35, 934 (1968).

[27] H. Poincaré, Rev. de Metaphys. et de Morale 6, 1 (1898).

[28] H. A. Lorentz, Old and New Problems in Physics (Russ. transl.), Nauka, 1970.

[29] Printsip otnositel'nosti. Sbornik rabot klassikov relyativizma (The Principle of Relativity. Collection of Classic Papers on Relativity by H. A. Lorentz, H. Poincaré, A. Einstein, and H. Minkowski), ONTI, M.-L., 1935.

[30] W. Voigt, Gött. Nachr. p. 41 (1887).

[31] W. Rindler, Am. J. Phys., 38, 1111 (1970).

[32] H. Poincaré, C. R. Ac. Sci., 140, 1504 (1905).

[33] H. Poincaré, Rend. Circ. Math. Palermo, 21, 129 (1906).

[34] Printsip otnositel'nosti (The Principle of Relativity), Atomizdat, M. 1973.

[35] Helle Zeit—dunkle Zeit, In Memoriam Albert Einstein, Hrsg. C. Seelig, Europa, Zurich, 1956.

[36] H. Weyl, Raum, Zeit, Materie, Springer-Verlag, Berlin, 1923.

Translated by S. Chomet