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Henri Poincaré, theoretical physics, and relativity theory in Paris

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1 Introduction

In studies of the emergence of relativity theory, historians have sought to characterize the reception of relativist ideas with respect to national communities of physicists and mathematicians, in an effort to reveal underlying features of these communities, such as their openness to new ideas, and their capacity for change. Stimulating this activity are the basic publication counts, that tell us that the reception of relativity theory in academic journals varied markedly from one country to another. Periodicals based in Germany accounted for roughly half of all relativist publications before 1916, while Germany-based authors published two of every five articles on relativity during the same period, and made up two-fifths of the total number of scientists (one hundred) contributing to relativity theory. France, the fifth most active country from a quantitative point of view, accounted for seven percent of relativist articles, and counted eight relativist scientists, or about a twelfth of the total.¹

Examination of the content of these publications and their context of production allows for a finer-grained understanding of the differences revealed by quantitative analyses, and gives rise to theories of reception. For example, scholars of the reception of relativity theory in Germany and England have proposed explanatory models in which the details of post-secondary training in physics are seen as decisive.² Historians of French physics consider the muted reception of relativity

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¹Of 662 publications on relativity theory in periodicals between 1905 and 1916, 323 were published in Germany; see Walter (1996, Tables 4.3–4).

²Pyenson 1987; Warwick 2003.

in France as a consequence of a pervasive positivist outlook among French scientists, which would have favored the development of mathematics, while leaving little intellectual space for the distinct melange of experimental acumen, physical and mathematical reasoning that characterized the work of a Boltzmann, a Lorentz, or an Einstein.³

Attention to the conceptual foundations of early relativist publications reveals a marked difference in approach on the part of two contributors in particular: Henri Poincaré and Albert Einstein. Understanding this difference in approach has occupied historians and philosophers of science for over half a century, without reaching a consensus on its significance for the history of physics.⁴ Poincaré's philosophical writings, published for the most part prior to the discovery of relativity, weigh heavily in these analyses, and according to one commentator, constituted an obstacle to the reception of Einstein's theory of relativity in France until the 1920s.⁵ By the same token, Poincaré's philosophical writings ought to have benefited his theory of relativity, but the above-mentioned publication counts indicate that they did not do so, either in France or elsewhere in the world.

The outlines of an alternative account of French contributions to relativity during the years from 1905 to 1912 are drawn in this paper. Poincaré's intellectual and institutional leadership in French physics at the turn of the twentieth century is reviewed, and related to the emergence of Paul Langevin as his successor. Drawing on quantitative data and previously-unexploited manuscripts from Parisian archives, the paper compares the fate in France of Poincaré's theory of relativity to that of the Einstein-Minkowski theory of relativity championed by Langevin, and links these events to Langevin's rise to leadership of French theoretical physics.

2 Poincaré and theoretical physics in Paris

Compared to the situation of French physics in the first decades of the nineteenth century, in 1898 the future did not appear promising to Henri Poincaré. His pessimism stemmed from a perceived mismatch between the cognitive habits of the French scientist and the turbulent state of theoretical physics brought about by the discoveries of the past decade, including the null-result of the Michelson-Morley ether-drift experiment, the discovery of x-rays, the electron, the Zeeman effect, and radioactivity. A certain boldness was called for to explain such results, and

³See Paty (1987, 115), Biezunski (1987, 184), and Pestre (1992, 117). On French isolationism in electrodynamics (and its exceptions), see Darrigol 2000, 352.

⁴A balanced overview of the "mystery of the Einstein-Poincaré connection" is provided by Darrigol (2004).

⁵See Borella 2002.

Poincaré feared that the French were not up to the task at hand, as he expressed it in an official report to the Paris faculty of science:

The French mind, avid of clarity and logic, is repugnant of excessively temerarious adventures.

A new type of physicist was called for, according to Poincaré, in order to “discern the simplicity of laws beneath the complexity of phenomena”.⁶ The type of physicist Poincaré had in mind, although probably not the archetype, was Jean Perrin, whose candidacy he evaluated for a lectureship in physical chemistry on the Paris faculty of science. To some extent, Poincaré may have described here his own approach to the laws of physics, although his prowess in mathematics clearly set him apart from even the most mathematically-sophisticated of his colleagues in physics.

Paris did not yet dispose of a chair in theoretical physics *per se*, and would not create one until 1928, when the Rockefeller Foundation volunteered to finance a new institute.⁷ The first French chair nominally devoted to theoretical physics dates from 1894, when the faculty of science in Bordeaux hired Pierre Duhem. This is not to say that theoretical physics was neglected in Paris. At the Paris faculty of science, the chair of probability calculus and mathematical physics, dating from 1834, was devoted to the subject. Poincaré held this chair for a decade, from 1886 to 1896, and single-handedly brought French theoretical physics to international attention. The work in theoretical optics and fluid mechanics by his successor Joseph Boussinesq, however, found little echo outside of France.⁸

For the sake of comparison, across the border, a modest institute for theoretical physics was created at the University of Berlin in 1889, at the behest of Hermann von Helmholtz, and by the turn of the century, such institutes had been created in Königsberg, Leipzig, Göttingen and Munich.⁹ At the turn of the twentieth century, only two of these institutes were led by full professors: Max Planck in Berlin, and Woldemar Voigt in Göttingen.¹⁰ There were other outstanding theorists in Germany, notably Paul Drude, Willy Wien, and Arnold Sommerfeld, but some of these theorists felt Germany had lost its preeminence in the field since the time of Gustav Kirchhoff.¹¹ Since the death of Heinrich Hertz in 1894, and Ludwig Boltzmann’s departure from Munich the same year, the brilliance of H. A. Lorentz in Leiden and Boltzmann in Vienna had cast shadows over their counterparts in Germany and France alike.

⁶Faculté des sciences de Paris, pièces annexes aux procès-verbaux, 1883–1903, 78–79, French National Archives. A transcription is available from the Henri Poincaré Papers website.

⁷Siegmund-Schultze 2001.

⁸Darrigol 2005, 239.

⁹Jungnickel & McCormmach 1986, vol. 2, 254.

¹⁰Schlote 2004, 86.

¹¹Jungnickel & McCormmach 1986, vol. 2, 159.

At least one theorist in Paris was prepared to meet the challenge posed by the recent results of experimental physics: Henri Poincaré. The fact that after 1896, Poincaré no longer occupied a chair of mathematical physics did not prevent him from lecturing and theorizing in this domain, just as earlier, he cultivated subjects of pure mathematics (function theory, algebraic topology), and celestial mechanics while nominally a professor of probability calculus and mathematical physics. Beginning in the late 1880s, Poincaré helped introduce Maxwell's electromagnetic theory to French readers, and in the late 1890s, he exhibited a keen interest in Lorentz's theory of electrons.¹² Interest in Lorentz's theory grew rapidly when Lorentz used it to explain the splitting of Sodium D lines in an external magnetic field, an unexpected phenomenon discovered in 1896 by Lorentz's former student, Pieter Zeeman (1865–1943). Poincaré communicated to the Paris Academy of Sciences a paper by Zeeman (1897) describing his discovery, and soon engaged with the explanation of the effect offered by Lorentz. Others in France soon took up studies of the Zeeman effect, including Alfred Cornu (1841–1902), Poincaré's former physics professor at the *École polytechnique*, and Alfred Liénard (1869–1958), a former student of Poincaré's, who taught mathematics and physics at the School of Mines in Saint-Étienne.

Poincaré's engagement with electrodynamics was enduring, and remarkably innovative, featuring applications of sophisticated mathematical methods (complex analysis, group theory), and the reformulation of key concepts of Maxwell's electromagnetic theory and Lorentz's electron theory, along with applications of these methods and theories. For example, in the 1890s, Poincaré was among the first to use retarded potentials in Maxwell's theory, and proposed the first electromagnetic theory of diffraction, which was soon extended by Arnold Sommerfeld. His demonstration of the recurrence theorem was recognized to have fundamental repercussions on physics, particularly for kinetic theory. He also provided a theory of multiple resonance for Hertzian oscillations, and the first exact solution of Maxwell's equations for charged particles in a strong magnetic field.¹³

By the turn of the century, Poincaré's contributions to physics had won the admiration and respect of his peers across Europe and in the USA. Poincaré was one of only two Frenchmen invited to contribute to a volume in honor of G.G. Stokes in 1899, alongside Cornu.¹⁴ The next year, Poincaré was one of the three Frenchmen on the scientific committee of the international physics congress organized in Paris by the French Society of Physics, and presided by Cornu. One of ten vice-presidents of the physics congress, Poincaré presided the international congress of mathematicians, which conveniently took place in Paris the same week in Au-

¹²See Darrigol 2000.

¹³Poincaré 1890, 1891b, 1891a, 1892–1893, 1897b.

¹⁴See Cambridge Philosophical Society, ed. (1900).

gust.¹⁵ The following year, Poincaré was elected vice-president of the French Society of Physics, and in 1902, served as its president. A few years later, the Society made Poincaré one of its ten honorary members.¹⁶

This recognition from Poincaré's peers in physics did not mean that his authority in physics went uncontested, either at home or abroad. There were those, like the Scottish natural philosopher P. G. Tait, who found his lectures on mathematical physics to be excessively analytical, and unreliable on foundational issues.¹⁷ Near the end of the decade, when Lorentz explained the Zeeman effect on the basis of his theory of electrons, Poincaré proposed an alternative formula, which was mathematically sound, but for Lorentz, unconvincing from a physical standpoint.¹⁸

In France, Poincaré's views on questions of mathematics or physics were very rarely challenged in public. The case of Marcel Brillouin (1854–1948) is instructive from this perspective. With doctoral degrees in mathematics and physics, Brillouin was named associate professor at the *École normale supérieure* in 1887. In the early 1890s, Brillouin dutifully pointed out what he thought was an error in the first edition of Poincaré's lectures on Maxwell's theory, concerning Hertzian waves. Poincaré's gentle private lesson led Brillouin to retract his criticism.¹⁹ In 1900, Brillouin replaced Joseph Bertrand as professor of general and mathematical physics at the *Collège de France*, and when a new edition of Poincaré's *Électricité et optique* appeared in 1901, Brillouin had only high praise for it.²⁰

At the turn of the century, Poincaré's physical acumen was severely tested, when Gabriel Lippmann's doctoral student, Victor Crémieu (1872–1935) published a result casting doubt on Rowland's effect, whereby, in line with Maxwell's theory, convected electricity produces a certain magnetic effect. Poincaré wrote the official report on Crémieu's thesis, communicated several of his results to the Paris Academy of Sciences, and argued that if the result was confirmed, Maxwell's theory would have to be abandoned. None of Europe's leading physicists gave any credence to Crémieu's findings, which if true, would have overturned the electron theories of Lorentz and Larmor, as well as Maxwell's theory. In France, Brillouin shared Poincaré's high opinion of Crémieu's results, but Poincaré's colleague at the Sorbonne, the physicist Henri Pellat (1850–1909) remained doubtful, as did

¹⁵C.-E. Guillaume and L. Poincaré, eds. (1900–1901).

¹⁶Three other French physicists had attained this status by 1909: Jules Violle, Gabriel Lippmann, and Émile-Hilaire Amagat; see *Bulletin de la société française de physique* (1908), p. 3*.

¹⁷See the review by P. G. Tait (1892) of Poincaré's *Thermodynamique* (1892), reedited with annotations (and Poincaré's replies) in Walter et al., eds, eds (2007, § 2-62).

¹⁸Poincaré 1897a; Buchwald 1985, 226.

¹⁹See Poincaré's correspondence with Brillouin in Walter et al., eds, 2007, § 2-12; Brillouin 1891a, 1891b.

²⁰Poincaré 1901; Brillouin 1901.

Poincaré's former teacher at the *École polytechnique*, Alfred Potier (1840–1905).

When Harold Pender, who was Rowland's last doctoral student, confirmed Rowland's effect in Baltimore, Poincaré saw to it that Pender and his equipment were transported to the Edmond Bouty's laboratory in Paris, in order to perform experiments side-by-side with Crémieu. Pender emerged victorious from the encounter; to the French Society of Physics Pender explained not only how the Rowland effect manifested itself, but why Crémieu's apparatus had failed to detect it.²¹ The result of the encounter suggests that Poincaré had misjudged the situation; nonetheless, he obtained what he required as a theoretical physicist: an experimental decision between Maxwellian and non-Maxwellian electrodynamics.

Pender and Crémieu's account of their parallel investigations of convected electricity appeared in a leading journal of French physics: the *Journal de physique théorique et appliquée (JPTA)*, founded in 1872. During the first decade of the twentieth century, the *JPTA*'s editorial board counted two professors of physics from the Paris faculty of science, Edmond Bouty and Gabriel Lippmann, along with a pair of senior theorists, Alfred Potier and Élie Mascart, neither of whom survived the decade. Filling out the editorial board were a trio of associate editors, former students of the *École normale supérieure*: Lucien Poincaré, Bernard Brunhes, and Georges Sagnac; and one non-Normalien associate editor, Marcel Lamotte, an associate professor of physics at Clermont-Ferrand, who like Brunhes had helped edit Poincaré's volumes on mathematical physics in the early 1890s.

The *JPTA* did not publish contributions in theoretical physics that involved sophisticated mathematical elaboration, in order to remain accessible to "isolated" physicists, which is to say, those out of range of science faculties and their libraries.²² This approach manifested itself in the selection of articles for publication, and in the abstracts of articles published abroad. More often than not, when an article featured a mathematical argument, the *JPTA* abstract revealed this fact alone, with no judgment of merit or meaning. Consequently, readers were ill-informed of current work in theoretical physics, beyond what might be guessed from reading the name of the author, and the title of the contribution.

There were other venues in France for publishing research in theoretical physics, including the *Annales de chimie et de physique* (or *ACP* for short), *Le Radium*, the *Annales scientifiques de l'École normale supérieure*, and the *Journal de mathématiques pures et appliquées*. The latter two journals attracted few papers on physics, unlike *Le Radium*, founded in 1904 by H. Becquerel, P. Curie, E. Rutherford, Ch.-E. Guillaume and others. *Le Radium* effectively competed for readers with the *JPTA*, providing translations of German and French contributions, and abstracts

²¹Pender & Crémieu 1903. Historical accounts include Indorato & Masotto 1989, and Walter et al., eds. 2007, § 2-17.

²²This was the policy announced by the *JPTA*'s founder, J.-C. Almeida, in the first issue of the review.

of various periodicals, until the two journals fused in 1920. The *ACP*, founded in 1816, attracted significant communications in the first decade of the twentieth century from Paul Langevin, Jacques Hadamard, Marcel Brillouin, and the latter's student, Jean Perrin. At the beginning of the decade, the *ACP* was directed by the venerable trio of Marcelin Berthelot, Élie Mascart, and Henri Moissan, none of whom were still alive in 1910. At the end of the first decade, a different trio of editors directed the *ACP*: the chemist Albin Haller (1849–1925) and his two colleagues on the Paris faculty of science, Lippmann and Bouty, who continued to edit the *JPTA*.

During this period the *ACP* published doctoral theses in physics, as well as extended summaries of experimental and theoretical investigations. Two examples may be mentioned here. One of these is the Swiss theorist Walter Ritz's long memoir, "Critical investigations in general electrodynamics", in which Ritz gave an overview of the work of Lorentz, Poincaré, Einstein, and others, and sketched an alternative approach to the electrodynamics of moving bodies, based on retarded potentials and a principle of superposition.²³ Another is Perrin's "Brownian motion and molecular reality", where he presented the results of experiments that confirmed Einstein's formula for Brownian motion of a particle in a fluid, work for which Perrin was awarded the Nobel Prize in physics in 1926.²⁴

The only other publishing outlet for research in theoretical physics in France, but one more widely cited than the *ACP* or any other French scientific journal, was the organ of the Paris Academy of Sciences, the *Comptes rendus hebdomadaires* (hereafter *CRAS*). This was where Poincaré published most often, averaging nine papers a year throughout his career, including a signal contribution to relativity theory on 6 June 1905. The *CRAS* enforced a page limit on its contributors, and Poincaré's four-page summary was no exception to the rule. The memoir summarized in the *CRAS* appeared in the *Rendiconti del Circolo matematico di Palermo*, a journal in which since 1888 Poincaré had published on the theory of differential equations, analytical mechanics, and algebraic topology. Until 1906, Poincaré published all his articles on physics (excluding notes in the *CRAS*) either in foreign journals, or in a Paris-based journal of electrical engineering, *Éclairage électrique*, on the editorial board of which he served beginning in 1899.

One consequence of this habit was that until 1906, Poincaré's latest research in theoretical and applied physics was known best to French electrical engineers, and readers of *CRAS* and foreign research journals. Students of physics knew Poincaré best through his lectures on mathematical physics, published in thirteen volumes (not counting translations to German, or reeditions). The effect of these volumes was described somewhat breathlessly by the mathematician (and former

²³Ritz 1908; Martínez 2004.

²⁴Perrin 1909; Nye 1972.

Poincaré student) Maurice d'Ocagne, for whom Poincaré had, in addition to being the world's premier theoretical astronomer,

... carved for himself an unequalled position as a theoretical physicist, projecting a new light, emanating from the most unexpected sources, upon every part of mathematical physics: heat, optics, electricity, elasticity, capillarity, etc. He has covered everything, renewed everything, extended everything. [...]

What is more, there are many experimentalists who make no mistake in recognizing all they owe to the theoretical views introduced to science by Mr. Poincaré, and who have quite often reoriented their laboratory investigations to the great benefit of the general advance of our knowledge. (Maurice d'Ocagne 1909, 541)

What d'Ocagne's remark suggests most clearly is the source of Poincaré's pre-eminence in French theoretical physics, and his influence on research agendas in experimental physics. Physicists who acknowledged such an influence included, among others in France, Henri Becquerel, René Blondlot, Gustave Le Bon, Paul Langevin, Georges Sagnac, Alfred Perot, and Victor Crémieu; in Geneva, Lucien de la Rive and Édouard Sarasin; in Kristiania (now Oslo), Kristian Birkeland.²⁵

While Poincaré's influence on the agenda of experimentalists is apparent, what can be said of his mark on the agenda of theorists? Some of the aforementioned experimentalists also wore a theorist's cap on occasion, like Birkeland, Langevin, and Sagnac. All three of these physicists published on subjects stemming from those taken up earlier by Poincaré, notably in the domains of Hertzian waves and electron theory; all were former students of Poincaré. According to another former student of Poincaré's, Arthur Korn, there was not a single physicist anywhere whose work had not found fundamental stimulation in Poincaré's lectures.²⁶

Poincaré is often characterized by historians as a leading critic of theories of physics, and indeed, his lectures in mathematical physics offered a magisterial discussion of rival theories in the several branches of physics, that compared relative strengths and weaknesses.²⁷ His lectures on Maxwell's theory were eagerly read in Germany (in German translation), and exercised a profound influence on the first German textbooks on Maxwellian electrodynamics.²⁸ Some of his non-technical analyses were reedited for a larger audience in the four anthologies of his epistemological writings on mathematics and the exact sciences edited by 1913,

²⁵Poincaré's interaction with experimental physicists is well-documented in his correspondence; see the introduction to Walter et al., eds, 2007.

²⁶Korn 1912.

²⁷Such a characterization is offered by Darrigol 1995, 2000.

²⁸See Darrigol 1993; 2000, 354.

which were widely read and appreciated by both specialists and the general reading public alike.²⁹ Poincaré's critical acumen in theoretical physics was appreciated by his peers, including Joseph Larmor, who contributed a preface to the English translation of the first of the anthologies: *Science and Hypothesis*.

On an international level, with the discovery of x-rays, the electron and radioactivity in the closing years of the nineteenth century, the physics of charged particles filled the pages of physics journals. French prowess in experimental microphysics received international recognition following work by Henri Becquerel and the Curies on radioactive matter, and René Blondlot on electrical convection, although the latter's reputation was later tarnished when what he called "N-rays" proved spurious. On the theoretical side, Poincaré and Alfred Liénard were among the first theorists to contribute to Lorentz's electron theory, and to apply it to dispersion phenomena and the Zeeman effect.³⁰ Outside of France, respected theorists at the turn of the twentieth century included, first and foremost, Lorentz in Leiden, Boltzmann in Vienna, Joseph Larmor and J.J. Thomson in Cambridge, Ernest Rutherford in Montreal, Paul Drude in Giessen, Max Planck in Berlin, Sommerfeld in Aachen, Wilhelm Wien in Würzburg, Woldemar Voigt, Emil Wiechert, Max Abraham, and Walther Nernst in Göttingen.

Critical analysis of physical theories was an activity at which Poincaré was skilled and accomplished, and for which he was amply rewarded. His contributions to physics, however, went well beyond writing textbooks and critiques of others' work, into the creative realm of theory construction. Among the theoretical physicists mentioned above, Sommerfeld and Abraham found significant inspiration in Poincaré's theories of physics. Sommerfeld's electromagnetic theory of diffraction of plane waves (1896) improved on Poincaré's groundbreaking paper of 1892, while Abraham borrowed on the Frenchman's conception of electromagnetic momentum to form his theory of electron dynamics.³¹ Last but not least, in the summer of 1907, Hermann Minkowski took up the elements of Poincaré's four-dimensional approach to relativity theory, in what became a game-changing theory of physics: the theory of spacetime.³²

The latter three contributions were among those cited in support of an ultimately unsuccessful campaign to award Poincaré the Nobel prize in physics in 1910, in addition to work on the propagation of Hertzian waves, and the theories of vibrating plates, rotating fluid masses, and electron stability. The failure of

²⁹According to Lebon (1912, 84), the first of these anthologies, entitled *La science et l'hypothèse* (1902), sold twenty thousand copies by 1911. On the composition of Poincaré's anthologies, see Rollet (2001, chap. 4).

³⁰See Buchwald 1985.

³¹Poincaré 1892–1893; Sommerfeld 1896, 2004. On Abraham's and Planck's theories see Miller 1980, 1981.

³²Poincaré 1906; Minkowski 1908; Walter 2007, 2008.

Poincaré's Nobel campaign reflects in part the still-uncertain status of the theory of relativity in 1910, and in fact, the Nobel committee never awarded a prize in recognition of the discovery of special relativity. In context, it is curious that a Nobel prize nomination emanating from the Paris Academy of Sciences in January 1910, and including among its signatories the Academy's permanent secretary for the mathematical sciences, Gaston Darboux, should feature work "of the highest importance" by Poincaré on the principle of relativity.³³ On 5 June 1905, Poincaré's precis of relativity theory appeared in the *Comptes rendus* of the Academy, announcing a longer work published in the Palermo *Rendiconti*.³⁴ Afterwards, no notes were published by anyone on this subject in the *Comptes rendus* until 7 February 1910, when results of cathode-ray deflection experiments by Charles-Eugène Guye and Simon Ratnowsky in Geneva appeared, tending to confirm Lorentz's predictions of velocity-dependent mass.³⁵ Contrary to Darboux's description, the publication record suggests that the theory of relativity was of little importance to French science, at least until February 1910.

What happened to the theory of relativity in France during the latter half of the first decade of the twentieth century? And how did Einstein's theory come to prominence in France in 1911? In the next section, I show that while Lorentz's theory was often discussed, alternative theories remained nearly invisible in France until 1911. The situation changed in 1911, as the final section will show.

3 The invisibility of Einstein's theory in France

In the scientific centers of Western Europe, physicists did not distinguish at first the theories of Lorentz, Poincaré, and Einstein. Of these three founders of relativity theory, Poincaré alone took care to identify the differences between his theory and that of Lorentz; Einstein's theory had not yet been published when he wrote his memoir. A year later, after Einstein's theory had been aired in the *Annalen der Physik*, Poincaré took care to explain to his students at the Sorbonne how his theory of relativity differed from that of Einstein, albeit without ever mentioning Einstein or his theory.

Poincaré performed a curious thought experiment for his students, in which a

³³See Darboux et al. to the Nobel Committee, ca. 1 January 1910, transcribed and annotated in Walter et al., eds, 2007, § 2-62. On the organization of the 1910 campaign, see Ph. Nabonnand's notes to the correspondence between Poincaré and G. Mittag-Leffler (Nabonnand 1999).

³⁴Poincaré 1905, 1906.

³⁵Guye and Ratnowsky (1910), originally submitted on 10 January 1910, and withdrawn by Guye, ostensibly to permit the inclusion of new data (Guye to Gaston Darboux, 30 January 1910, Archives of the Academy of Sciences, session folder, 7 February 1910).

pair of inertial observers, one at rest, the other moving away in a straight line at constant speed, describe the form of a locus of light at a certain instant of time. An observer at rest with respect to the ether judges the light locus to have the form of a sphere, the radius of which increases with the speed of light. Observers in motion with respect to the ether, Poincaré explained, would conclude that the light locus at any instant of time (as determined via co-moving light-synchronized clocks) is represented by an ellipsoid of rotation, elongated in the direction of observer motion with respect to the ether. In Einstein's theory, by contrast, the light locus at any given instant of time (as determined via co-moving light-synchronized clocks) is always represented by a sphere.³⁶ After presenting his view of relativity to his students, Poincaré published his light-ellipsoid theory of relativity in France's leading popular-science biweekly, the *Revue générale des sciences pures et appliquées*. He did not mention Einstein's theory, and in the *Revue générale* no one else did, either, until Maurice Lémeray wrote of "Einstein's beautiful results" four years later.³⁷

Poincaré's silence with respect to Einstein's theory has been the subject of much historical speculation, and will not concern us here. Instead, let us ask why no one else in France saw fit to mention Einstein's theory in print before 1911. And to begin with, let us investigate why one person in particular, Paul Langevin, did not mention Einstein's theory in print before 1911. Recall that in 1905 Langevin proposed an electron theory similar in some respects to that of Alfred Heinrich Bucherer, featuring an electron model of constant volume, and velocity-dependent shape, and that Poincaré showed Langevin's theory to be incompatible with relativity. Langevin acknowledged Poincaré's judgment of his theory, but did not give it up until the experimental results presented by A.H. Bucherer in September 1908 persuaded him to do so.³⁸ To put it briefly, until the fall of 1908 there were several plausible alternatives available to relativity theory, some of which enjoyed, like Abraham's rigid-electron theory, better empirical support in some tests than did the theory of relativity.³⁹

Einstein was not unknown in French physics circles, and his name was cited in contexts other than relativity in the period from 1905 to 1910. In kinetic theory, for example, Einstein's formula of 1905 for specific heat was promoted by Jean Perrin in 1908, and referred to simply as "Einstein's formula". A look at the abstracts published by the *JPTA* from 1905 to 1911 reveals that the "Abraham theory" of the electrodynamics of moving bodies was mentioned twice, the "Einstein theory"

³⁶See my forthcoming paper in *Einstein Studies*. For alternative explanations of Poincaré's light-ellipsoid, see Cuvaj (1970, 74) and Darrigol (2006, 17–19).

³⁷Poincaré 1908; Lémeray 1912.

³⁸See Langevin's *Notice sur les travaux scientifiques* (1908, 35).

³⁹On the choice between alternative theories of the electrodynamics of moving bodies circa 1905, see Darrigol (2000, 391).

three times, and the “Poincaré theory” or “Lorentz-Poincaré theory” four times. One notices that Poincaré’s theory never stood alone in these abstracts, but was always accompanied by a reference to Lorentz’s theory, which was mentioned much more often than any other, garnering a total of twenty-two independent occurrences.

Also, the paucity of detail in *JPTA* abstracts on relativity and electron theory, compared with that provided for other subjects, suggests a certain lack of comprehension or interest on the part of the abstract writer. A general ignorance of and disinterest in relativity theory was not unique to French physicists, as even in Germany, publication numbers remained modest in this area until 1909, when they began to climb rapidly (see Fig. 2). One difficulty for relativity theory was its poor performance in electron-deflection experiments, which led many to believe that relativity theory was empirically untenable. In a discussion of electron theory in 1906, for example, Paul Ehrenfest considered Lorentz’s theory to have been definitively disproved by experiment, and Ehrenfest’s opinion was duly related by Léon Bloch for readers of *Le Radium*.⁴⁰ In such circumstances, it is a wonder that any physicist bothered learning relativity theory before the end of 1908.

After an experimental confirmation of relativity theory was announced in September 1908, the incentive to learn the theory, and to investigate its consequences naturally increased. What is curious in the French context is that apart from Poincaré, no other physicist took up relativity, until Paul Langevin lectured on the subject at the Collège de France in 1910–1911. According to Poincaré’s own report, he pursued a relativistic theory of elastic collisions, but deemed his results unworthy of publication. As he explained it to a Berlin audience in late 1910, the lack of such a theory was one reason why the new mechanics of relativity could not be considered “definitively grounded”.⁴¹ In front of French audiences, Poincaré offered a different message, designed to reassure those worried about overturning Newtonian mechanics: the “old mechanics”, Poincaré announced, was still the one for “our practical life and our terrestrial technology”.⁴²

Poincaré’s measured consideration of the theory he helped create may have dissuaded a few junior French theorists from following in his tracks, but not Paul Langevin.⁴³ As a student of Poincaré’s 1896 lectures on the elastic theory of light, Langevin had learned how a certain theorist referred to as “Somerset” extended

⁴⁰Ehrenfest 1906; *Le Radium* 3, 1906, p. 148.

⁴¹Poincaré 1910, 115–116.

⁴²“Quoi qu’il en soit, d’ailleurs, elle restera la mécanique des vitesses très petites par rapport à la vitesse de la lumière, la mécanique donc de notre vie pratique et de notre technique terrestre.” Plenary lecture, 3 August, 1909, to the meeting of the French Association for the Advancement of Science in Lille (Poincaré 1909).

⁴³On Langevin’s relation to Poincaré and Einstein, see Paty (2002).

Poincaré’s theory of polarization by diffraction.⁴⁴ Ten years later, on the strength of this work, and more recent contributions to electron theory, this same theorist – better known as Arnold Sommerfeld – was named to the chair of theoretical physics in Munich, formerly held by Boltzmann.⁴⁵ Sommerfeld was in charge of the physics volume of Felix Klein’s planned six-volume *Encyclopedia of Mathematical Sciences with Applications*, the first entries of which appeared in 1903.⁴⁶ On 16 April, 1906, Sommerfeld informed Langevin that Klein had agreed to let him co-edit the French version of the physics volume with Jean Perrin, a task that would occupy the two Frenchmen for nearly a decade.⁴⁷ Along with their editing duties, Sommerfeld and Langevin shared for several years the electromagnetic world-view, which promised a unification of all forces on an electromagnetic basis. But as mentioned above, in late 1908, theory and experiment conspired to convince Langevin of the cogency of the theory of relativity.

As a former student of Poincaré’s, and an occasional dinner guest at his flat in Paris, Langevin would have been at first glance a natural candidate to take up Poincaré’s theory of relativity. A similar remark may be made about Sommerfeld, who did not hear Poincaré’s lectures at the Sorbonne, but who admired and emulated his approach to physics. Whatever affinity Sommerfeld and Langevin had with Poincaré and his science, they both preferred the Einstein-Minkowski theory to that of Poincaré. For Sommerfeld, it was Minkowski’s spacetime theory that persuaded him of the cogency of relativity theory.⁴⁸ Langevin, too, was impressed by Minkowski’s theory, and by Sommerfeld’s related four-dimensional vector algebra and analysis, which he presented in his 1910–1911 lectures at the Collège de France.⁴⁹ The elements of spacetime theory were readily available to French readers by then, since in late 1909, a pair of former students of the *École normale supérieure* had translated Minkowski’s 1908 lecture “Space and time” for publication in the *Annales scientifiques de l’École normale supérieure*.⁵⁰

Like Poincaré, Langevin felt that the ether was not a wholly superfluous con-

⁴⁴Fonds Langevin, Notebook “Poincaré Élasticité et optique III 1896”, carton 123, Bibliothèque de l’École supérieure de physique et de chimie industrielle, Paris. In a later appreciation of Poincaré’s contributions to physics, Langevin recalled Poincaré’s lectures on optics, which showed how Sommerfeld “brilliantly followed a path” opened by Kirchhoff and Poincaré via complex analysis; see Langevin (1913, 691).

⁴⁵Eckert 1984.

⁴⁶See Eckert and Märker, eds, 2001–2004, vol. 1, p. 40.

⁴⁷Fonds Langevin, op. cit., carton 76.

⁴⁸Walter 1999, 70.

⁴⁹Sommerfeld 1910a, 1910b. Likewise, Minkowski admired Langevin’s contributions to the kinetic theory of gases; see Minkowski to Felix Klein, 1 Oct. 1906, Klein Nachlass, Niedersächsische Staats- und Universitätsbibliothek.

⁵⁰Minkowski (1909), translated from the German original by Aimé Hennequin and Joseph Marty. On Poincaré’s response to Minkowski’s theory, see Walter (2009).

cept for modern physics. One auditor of Langevin's lectures, Léon Brillouin, recorded Langevin's remark on this subject:

The very notion of the ether loses its sense, says Einstein – this is an exaggeration. We can't discern our speed with respect to the ether, but we can discern [our] accelerations and rotations.⁵¹

On the subject of light-waves, Langevin maintained on another occasion that a spherical light-wave in one inertial frame is actually spherical for all inertial observers.⁵² The latter view signals Langevin's break with Poincaré, for whom the light locus only *appeared* spherical for observers in motion with respect to the ether. In fact, Langevin fully agreed with Einstein and Minkowski that the universal validity of the principle of relativity implied a new view of space and time, and he defended this view publicly, beginning in 1911.

To put Langevin's defense of Einstein-Minkowski theory into historical perspective, let us examine some publication numbers. In 1911, publication of articles on relativity theory in periodicals worldwide hit a peak at one hundred and seventeen titles, after a sustained increase in scientific interest beginning in 1909 (see Fig. 1). This increase is reflected on a modest scale, and with a delay of a year or two, in the United Kingdom and in France. Figure 2 shows the evolution of publication numbers from 1905 to 1916 for the top five nations in article productivity. French numbers rose slightly in 1911, and peaked at thirteen articles in 1913.⁵³

Bare publication numbers tell us nothing of the causes of their annual fluctuation, a fact which leads us back to the *JPTA* abstracts. In 1911, "Einstein theory" is mentioned in nine abstracts, six of which mention no other theory. Next comes "Lorentz theory", with five mentions, followed by one mention each for Poincaré and Minkowski. The novelty in 1911 French physics, according to this source, was Einstein's theory of relativity. A closer look at the *JPTA* abstracts, however, suggests that these citation figures be treated with prudence. In 1911, the

⁵¹"La notion même d'éther perd son sens, dit Einstein—c'est exagéré. On ne peut saisir notre vitesse p[ar] rapp[ort] à l'éther, mais on peut saisir les accélérations et rotations." Léon Brillouin, Notebook "Cours de Relativité au Collège de France 1910–1911", Léon Brillouin Papers, Box 7, folder 8, American Institute of Physics, Niels Bohr Library. Langevin made the same point – without mentioning Einstein by name – in a lecture delivered on 10 April 1911 to the Fourth International Congress of Philosophy in Bologna, where Poincaré was present; see Langevin (1911, 233).

⁵²Langevin 1912, 335.

⁵³These publication numbers do not take into account an author's nationality or workplace. Data correlating the production of articles on relativity to nationality of the writer is presented in Walter (1996), which is also the source of the data in the figures presented here, augmented by fifty titles gleaned from the author's subsequent research. The publication database is freely available from the author's homepage.

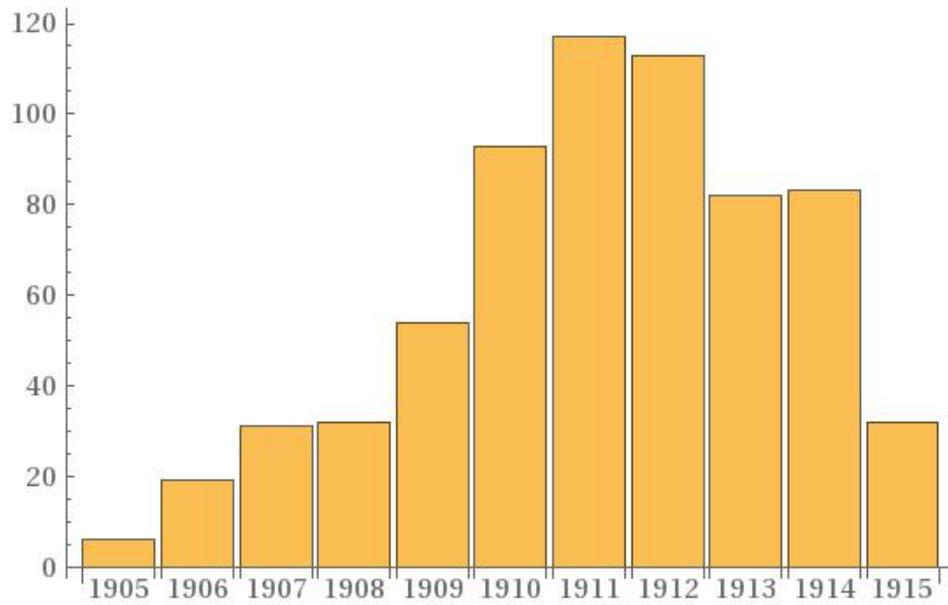


Figure 1: Global publication of articles on relativity in periodicals, 1905–1916. $N = 662$. Source: Walter (1996).

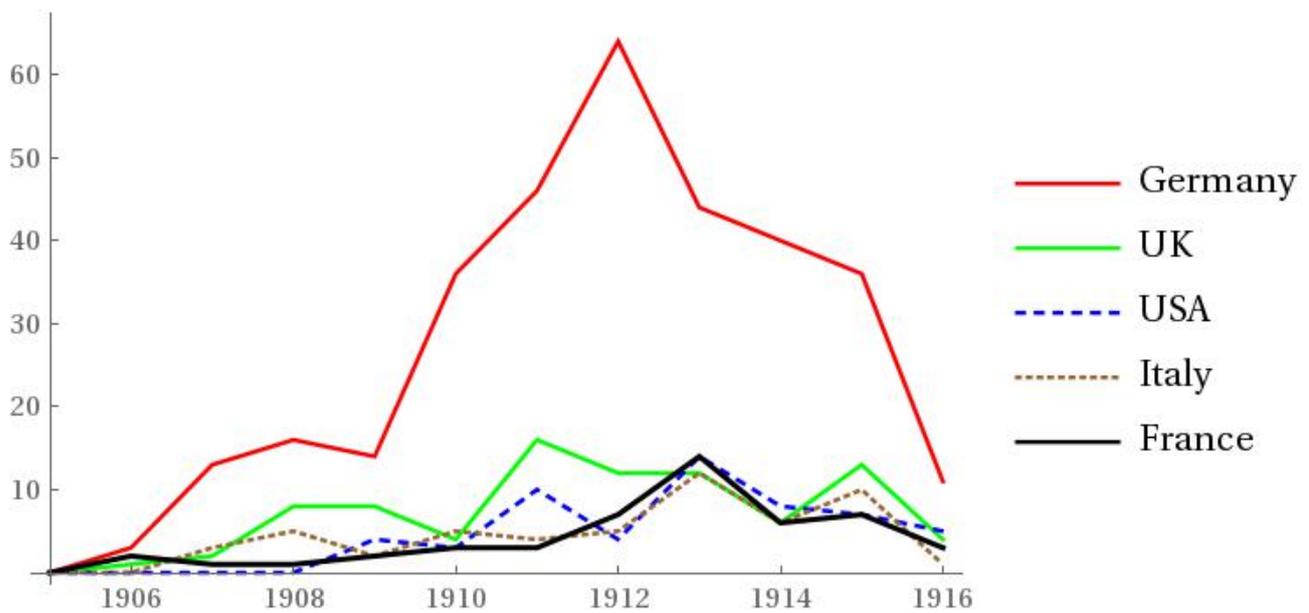


Figure 2: Publication of articles on relativity in periodicals, 1905–1916: Germany, United Kingdom, USA, Italy, France. $N = 566$. Source: Walter (1996).

JPTA recruited a new abstract writer, a nautical engineer from Antibes, Maurice Lémeray (b. 1860), and assigned him articles on relativity published in German or English. A science teacher turned warship designer, Lémeray was himself a prolific writer on relativity, having published more articles in 1911 and 1912 than any other Frenchman. His writings show no marked allegiance to either Einstein or Poincaré, but agree in general with Einstein's theory. Indeed, Lémeray was the first to cite Einstein's publications on relativity in the *Comptes rendus*, in a note communicated to Academy of Sciences by Poincaré, whose name Lémeray was careful to cite.⁵⁴ In summary, the increased number of citations of Einstein's theory in the 1911 *JPTA* abstracts has more to do with staff changes at the *JPTA* than with any bound in recognition of Einstein's contributions to relativity among French physicists.

The details of Lémeray's rise to prominence in France throw light on the reception of Einstein's theory. Archival documents reveal that Lémeray sought the Paris Academy's approval for his work on relativity as early as September 1910, when he submitted a manuscript to Gaston Darboux, one of the Academy's permanent secretaries.⁵⁵ Judged unfit for publication, the four-page note entitled "On the Lorentz transformation" purported to demonstrate Lorentz's formulas for local time, length contraction, and transverse and longitudinal mass from Einstein's twin postulates of relativity and universal lightspeed invariance, and dimensional analysis. Lémeray insisted that his results were free of "any hypothesis on the mechanism of phenomena or on any electrical theory", and he cited only one paper: Einstein's first French-language publication on relativity in the *Archives de Genève*. His purported demonstration of time dilation from the longitudinal Doppler effect for lightwaves, however, involved circular reasoning, and probably rendered his manuscript unpublishable. What this episode suggests is that the invisibility of Einstein's theory in France until 1911 was due in part to the paucity of physicists prepared to meet the cognitive challenge of Einstein's theory, combined with the existence of a rigorous manuscript review process. Similar instances of manuscript rejection in this area of physics took place elsewhere, of course, Germany included.⁵⁶

4 Epilogue

With assistance from Perrin, Langevin, and Lémeray, Einstein's star was ascending over France by 1911. In November, 1911, Poincaré recommended him for a

⁵⁴Lémeray 1911.

⁵⁵Session folder, 3 October 1910, Archives of the Academy of Sciences, Paris.

⁵⁶See, for example, Lewis Pyenson's review (1985, chap. 8) of Max Planck's rejection of papers submitted to the *Annalen der Physik*.

chair in theoretical physics at the ETH in Zurich, commenting that “the future will show more and more what Mr. Einstein’s value is”, and in January 1912, Einstein was named to this chair, and elected a non-resident council member of the French Society of Physics.⁵⁷ In May, 1912, Poincaré admitted that the new mechanics of relativity could serve as a basis for a redefinition of time and space, thereby recognizing the philosophical significance of Einstein-Minkowski theory.⁵⁸ This was a giant step for Poincaré, but it came too late to make any difference for physics in France. By 1912, the leading French theorists, including Langevin, and the mathematicians Émile Borel and Élie Cartan, had already adopted Einstein-Minkowski theory.⁵⁹

The engagement of Borel, Cartan, and other French mathematicians with the theory of relativity followed an example set in Germany by Minkowski, Gustav Herglotz, and Felix Klein. To some extent, the contributions of French mathematicians compensated the feeble participation of French theoretical physicists – Poincaré excepted – in the construction and diffusion of relativity. Once again, Langevin appears to have been instrumental in attracting the attention of French mathematicians to the study of Einstein-Minkowski theory. His role in introducing Einstein’s theory to French scientists was later described by Jacques Hadamard as follows:

It is well known that, under the powerful leadership of Mr. Langevin, the young French physicists rallied to the new movement of ideas created by Mr. Einstein’s discoveries. But cooperation with this movement was no less important to mathematicians, whose doctrines the new theory brought into play to a higher degree than any other previous physical conception. This is just what geometers like Mr. Borel understood from the beginning. (Hadamard 1922, i)

What Hadamard’s remark suggests is that for us to understand the reception of relativity in France, we need to go beyond the small circle of theoretical physicists, and examine how mathematicians came to engage with the theory.

In this essay, Poincaré’s influence on theoretical physicists in France has been discussed, but not his interaction with mathematicians. Nonetheless, even in the restricted domain of theoretical physics in France, the interactions between mathematics and physics appear decisive for the reception of relativity theory. The systematic appeal to sophisticated and powerful mathematics in the construction and

⁵⁷Poincaré to Pierre Weiss, ca. November, 1911, transcribed in Walter et al., eds, 2007, § 2-59-3; *Procès-verbaux de la Société française de physique* 1912, p. 9.

⁵⁸Poincaré 1912; Walter 2009.

⁵⁹See Borel’s 1913 lectures on Minkowski spacetime at the Sorbonne (Borel 1914), and Cartan’s lecture on the “new kinematics” of relativity before the French Society of Mathematics (Cartan 1912).

elaboration of physical theory was a legacy Poincaré bestowed on all his physics students. In this sense, Poincaré may be said to have smoothed the path in France for both Paul Langevin and the Einstein-Minkowski theory of relativity, at the expense of his own approach to relativity.

References

- Biezunski, M. Einstein's reception in Paris in 1922. In Glick (1987), 169–188, 1987.
- Borel, E. *Introduction géométrique à quelques théories physiques*. Paris: Gauthier-Villars, 1914. URL <http://ia310807.us.archive.org/1/items/introductiongo00boreuoft/>.
- Borella, V. Les écrits épistémologiques de Poincaré, obstacles à la diffusion de la relativité. *Revue d'histoire des sciences* 55(1) (2002): 45–81. URL http://www.persee.fr/web/revues/home/prescript/article/rhs_0151-4105_2002_num_55_1_2143?_Prescripts_Search_isPortletOuvrage=false.
- Brillouin, M. L. Compte rendu : H. Poincaré, Électricité et optique II. *Revue générale des sciences pures et appliquées* 2 (1891a): 268. URL <http://gallica.bnf.fr/ark:/12148/bpt6k213929b/f236.image>.
- . Compte rendu et analyse : Henri Poincaré, Électricité et optique. *Bulletin des sciences mathématiques* 15 (1891b): 129–146. URL <http://gallica.bnf.fr/ark:/12148/bpt6k486250q/f245.image>.
- . Compte rendu et analyse : Henri Poincaré, Électricité et optique. *Bulletin des sciences mathématiques* 25 (1901): 118–127. URL <https://archive.org/stream/s2bulletindessci25fran#page/n121/mode/2up>.
- Buchwald, J. Z. *From Maxwell to Microphysics*. Chicago: University of Chicago Press, 1985.
- Cambridge Philosophical Society, ed. *Memoirs Presented to the Cambridge Philosophical Society on the Occasion of the Jubilee of Sir George Gabriel Stokes*. Cambridge: Cambridge University Press, 1900. URL <https://archive.org/details/memoirspresente00socigoog>.
- Cartan, E. Sur les groupes de transformations de contact et la cinématique nouvelle. *Société mathématique de France, Comptes rendus des séances* (1912): 23.

- Cuvaj, C. *A History of Relativity: The Role of Henri Poincaré and Paul Langevin*. Ph.D. dissertation, Yeshiva University, New York, 1970.
- Darrigol, O. The electrodynamic revolution in Germany as documented by early German expositions of ‘Maxwell’s theory’. *Archive for History of Exact Sciences* 45 (1993): 189–280.
- . Henri Poincaré’s criticism of fin de siècle electrodynamics. *Studies in History and Philosophy of Modern Physics* 26 (1995): 1–44.
- . *Electrodynamics from Ampère to Einstein*. Oxford: Oxford University Press, 2000.
- . The mystery of the Einstein-Poincaré connection. *Isis* 95(4) (2004): 614–626.
- . *Worlds of Flow: A History of Hydrodynamics from the Bernoullis to Prandtl*. Oxford: Oxford University Press, 2005.
- . The genesis of the theory of relativity. In *Einstein, 1905–2005*. Edited by T. Damour, O. Darrigol, B. Duplantier, and V. Rivasseau, 1–32. Progress in Mathematical Physics 47. Basel: Birkhäuser, 2006.
- Eckert, M. and Märker, K., eds. *Arnold Sommerfeld: Wissenschaftlicher Briefwechsel*. 2 vols. Diepholz: GNT-Verlag, 2001–2004.
- Eckert, M. and Pricha, W. Boltzmann, Sommerfeld und die Berufungen auf die Lehrstühle für theoretische Physik in Wien und München 1890–1917. *Mitteilungen der Österreichischen Gesellschaft für Geschichte der Naturwissenschaften* 4 (1984): 101–119.
- Ehrenfest, P. Zur Stabilitätsfrage bei den Bucherer-Langevin-Elektronen. *Physikalische Zeitschrift* 7 (1906): 302–303.
- Glick, T. F., ed. *The Comparative Reception of Relativity*. Dordrecht: Reidel, 1987.
- Guillaume, C.-E. and Poincaré, L., eds. *Rapports présentés au congrès international de physique*. 4 vols. Paris: Gauthier-Villars, 1900–1901. URL <http://www.archive.org/stream/rapportsprresents00physgoog#page/n10/mode/2up>.
- Guye, C.-E. and Ratnowsky, S. Sur la variation de l’inertie de l’électron en fonction de la vitesse dans les rayons cathodiques et sur le principe de relativité. *Comptes rendus hebdomadaires de l’Académie des sciences de Paris* 150(6) (1910): 326–329.

- Hadamard, J. Préface. In *G. Juvet, Introduction au calcul tensoriel et au calcul différentiel absolu*, i–ii. Paris: Blanchard, 1922.
- Indorato, L. and Masotto, G. Poincaré’s role in the Crémieu-Pender controversy over electric convection. *Annals of Science* 46(2) (1989): 117–163. URL <http://dx.doi.org/10.1080/00033798900200161>.
- Jungnickel, C. and McCormmach, R. *Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein*. 2 vols. Chicago: University of Chicago Press, 1986.
- Korn, A. Henri Poincaré (1854–1912). *Sitzungsberichte der Berliner mathematischen Gesellschaft* 12 (1912): 3–13.
- Langevin, P. *Notice sur les Travaux Scientifiques*. Paris: n.p., 1908.
- . L’évolution de l’espace et du temps. *Scientia (Rivista di Scienza)* 10(29) (1911): 31–54. URL http://amshistorica.unibo.it/diglib.php?inv=7&int_ptnum=10&term_ptnum=39&format=jpg.
- . Le temps, l’espace et la causalité dans la physique moderne. *Bulletin de la Société française de philosophie* 12 (1912): 1–28.
- . L’œuvre d’Henri Poincaré : le physicien. *Revue de métaphysique et de morale* 21 (1913): 675–718. URL <http://gallica.bnf.fr/ark:/12148/bpt6k111418/f93.image>.
- Lebon, E. *Henri Poincaré : Biographie, bibliographie analytique des écrits*. Paris: Gauthier-Villars, 2d edition, 1912. URL <http://www.gutenberg.org/files/32948/32948-h/32948-h.htm>.
- Lémeray, M. Le principe de relativité et les forces qui s’exercent entre les corps en mouvement. *Comptes rendus hebdomadaires de l’Académie des sciences de Paris* 152(22) (1911): 1465–1468.
- . Le principe de relativité et la mécanique. *Revue générale des sciences pures et appliquées* 23(5) (1912): 174–183.
- Martínez, A. A. Ritz, Einstein, and the emission hypothesis. *Physics in Perspective* 6 (2004): 4–28.
- Miller, A. I. On some other approaches to electrodynamics in 1905. In *Some Strangeness in the Proportion*. Edited by H. Woolf, 66–91. Reading, MA: Addison-Wesley, 1980.

- . *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretation*. Reading, MA: Addison-Wesley, 1981.
- Minkowski, H. Die Grundgleichungen für die electromagnetischen Vorgänge in bewegten Körpern. *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen* (1908): 53–111. URL <http://gdz.sub.uni-goettingen.de/en/dms/load/img/?PPN=GDZPPN00250152X>.
- . Espace et temps. *Annales scientifiques de l'École normale supérieure* 26 (1909): 499–517.
- Nabonnand, P., ed. *La correspondance d'Henri Poincaré, Volume 1: La correspondance entre Henri Poincaré et Gösta Mittag-Leffler*. Basel: Birkhäuser, 1999. URL <http://henripoincarepapers.univ-lorraine.fr/chp/1alpha.html>.
- Nye, M. J. *Molecular Reality: A Perspective on the Scientific Work of Jean Perrin*. Amsterdam: Elsevier, 1972.
- Ocagne, M. d. Biographie du conférencier M. Henri Poincaré. *Journal de l'Université des Annales* 3 (1909): 539–541.
- Paty, M. The scientific reception of relativity in France. In Glick (1987), 113–167, 1987.
- . Poincaré, Langevin et Einstein. *Épistémologiques* 2 (2002): 33–73.
- Pender, H. and Crémieu, V. Recherches contradictoires sur l'effet magnétique de la convection électrique. *Bulletin des séances de la Société française de physique* (1903): 136–162.
- Perrin, J. Mouvement brownien et réalité moléculaire. *Annales de chimie et de physique* 18 (1909): 1–114.
- Pestre, D. *Physique et physiciens en France 1918–1940*. Paris: Éditions des archives contemporaines, 2d edition, 1992.
- Poincaré, H. Sur le problème des trois corps et les équations de la dynamique. *Acta mathematica* 13 (1890): 1–270. URL <http://henripoincarepapers.univ-lorraine.fr/chp/hp-pdf/hp1890am.pdf>.
- . Sur la résonance multiple des oscillations hertziennes. *Archives des sciences physiques et naturelles* 25 (1891a): 609–627. URL <http://henripoincarepapers.univ-lorraine.fr/chp/hp-pdf/hp1891aga.pdf>.

- . Sur la théorie des oscillations hertziennes. *Comptes rendus hebdomadaires de l'Académie des sciences de Paris* 113 (1891b): 515–519. URL <http://henripoincarepapers.univ-lorraine.fr/chp/hp-pdf/hp1891crf.pdf>.
- . *Thermodynamique*. Paris: Georges Carré, 1892. URL <http://www.archive.org/details/thermodynamique00poingoog>.
- . Sur la polarisation par diffraction. *Acta mathematica* 16 (1892–1893): 297–339. URL <http://henripoincarepapers.univ-lorraine.fr/chp/hp-pdf/hp1892am.pdf>.
- . La théorie de Lorentz et les expériences de Zeeman. *Éclairage électrique* 11 (1897a): 481–489.
- . Sur la polarisation par diffraction. *Acta mathematica* 20 (1897b): 313–355. URL <http://henripoincarepapers.univ-lorraine.fr/chp/hp-pdf/hp1897am.pdf>.
- . *Électricité et optique: la lumière et les théories électrodynamiques*. Paris: Carré et Naud, 1901. URL <http://www.archive.org/details/electriciteetopt019479mbp>.
- . Sur la dynamique de l'électron. *Comptes rendus hebdomadaires de l'Académie des sciences de Paris* 140 (1905): 1504–1508. URL [http://fr.wikisource.org/wiki/Sur_la_dynamique_de_l%27electron_\(juin\)](http://fr.wikisource.org/wiki/Sur_la_dynamique_de_l%27electron_(juin)).
- . Sur la dynamique de l'électron. *Rendiconti del Circolo Matematico di Palermo* 21 (1906): 129–176. URL <http://henripoincarepapers.univ-lorraine.fr/chp/hp-pdf/hp1906rp.pdf>.
- . La dynamique de l'électron. *Revue générale des sciences pures et appliquées* 19 (1908): 386–402. URL <http://henripoincarepapers.univ-lorraine.fr/chp/hp-pdf/hp1908rg.pdf>.
- . La mécanique nouvelle. *Revue scientifique* 12 (1909): 170–177. URL <http://henripoincarepapers.univ-lorraine.fr/chp/text/hp1909rs.html>.
- . Die neue Mechanik. *Himmel und Erde* 23 (1910): 97–116. URL <http://henripoincarepapers.univ-lorraine.fr/chp/text/hp1910he.html>.

- . L'espace et le temps. *Scientia (Rivista di Scienza)* 12(25) (1912): 159–170. URL <http://henripoincarepapers.univ-lorraine.fr/chp/text/hp1912sca.html>.
- Pyenson, L. *The Young Einstein: The Advent of Relativity*. Bristol: Adam Hilger, 1985.
- . The relativity revolution in Germany. In Glick (1987), 59–111, 1987.
- Ritz, W. Recherches critiques sur l'électrodynamique générale. *Annales de chimie et de physique* 13 (1908): 145–275.
- Rollet, L. *Henri Poincaré, des mathématiques à la philosophie : étude du parcours intellectuel, social et politique d'un mathématicien au début du siècle*. Lille: Éditions du Septentrion, 2001. URL http://tel.archives-ouvertes.fr/docs/00/13/78/59/PDF/These_Rollet.pdf.
- Schlote, K.-H. Zu den Wechselbeziehungen zwischen Mathematik und Physik an der Universität Leipzig in der Zeit von 1830 bis 1904/05. *Abhandlungen der Sächsischen Akademie der Wissenschaften zu Leipzig, Mathematisch-naturwissenschaftliche Klasse* 63(1) (2004): 1–132.
- Siegmund-Schultze, R. *Rockefeller and the Internationalization of Mathematics between Two World Wars: Documents and Studies for the Social History of Mathematics in the 20th Century*. Basel: Birkhäuser, 2001.
- Sommerfeld, A. Mathematische Theorie der Diffraction. *Mathematische Annalen* 47 (1896): 317–374. URL <http://gdz.sub.uni-goettingen.de/dms/load/img/>.
- . Zur Relativitätstheorie, I: Vierdimensionale Vektoralgebra. *Annalen der Physik* 337 (1910a): 749–776.
- . Zur Relativitätstheorie, II: Vierdimensionale Vektoranalysis. *Annalen der Physik* 338 (1910b): 649–689.
- . *Mathematical Theory of Diffraction*. Boston: Birkhäuser, 2004.
- Tait, P. G. Poincaré's Thermodynamics. *Nature* 45 (1892): 245–246. URL <http://henripoincarepapers.univ-lorraine.fr/chp/text/tait0.html>.

- Walter, S. A. *Hermann Minkowski et la mathématisation de la théorie de la relativité restreinte, 1905–1915*. Ph.D. dissertation, Université Paris 7, Paris, 1996. URL <http://scottwalter.free.fr/papers/walter-thesis-1996.pdf>.
- . Minkowski, mathematicians, and the mathematical theory of relativity. In *The Expanding Worlds of General Relativity*. Edited by H. Goenner, J. Renn, T. Sauer, and J. Ritter, 45–86. Einstein Studies 7. Boston/Basel: Birkhäuser, 1999. URL <http://scottwalter.free.fr/papers/1999-mmm-walter.html>.
- . Breaking in the 4-vectors: the four-dimensional movement in gravitation, 1905–1910. In *The Genesis of General Relativity, Volume 3*. Edited by J. Renn and M. Schemmel, 193–252. Berlin: Springer, 2007. URL <http://scottwalter.free.fr/papers/2007-genesis-walter.html>.
- . Hermann Minkowski’s approach to physics. *Mathematische Semesterberichte* 55(2) (2008): 213–235. URL <http://scottwalter.free.fr/papers/2008-mathsmb-walter.html>.
- . Hypothesis and convention in Poincaré’s defense of Galilei spacetime. In *The Significance of the Hypothetical in the Natural Sciences*. Edited by M. Heidelberger and G. Schiemann, 193–219. Berlin: Walter de Gruyter, 2009. URL <http://scottwalter.free.fr/papers/2009-heidelberger-walter.html>.
- Walter, S. A., Bolmont, E., and Coret, A., eds. *La correspondance d’Henri Poincaré, Volume 2: La correspondance entre Henri Poincaré et les physiciens, chimistes et ingénieurs*. Basel: Birkhäuser, 2007. URL <http://henripoincarepapers.univ-lorraine.fr/chp/2alpha.html>.
- Warwick, A. C. *Masters of Theory: Cambridge and the Rise of Mathematical Physics*. Chicago: University of Chicago, 2003.
- Zeeman, P. Lignes doubles et triples dans le spectre, produites sous l’influence d’un champ magnétique extérieur. *Comptes rendus hebdomadaires de l’Académie des sciences de Paris* 124 (1897): 1444–1445. URL <http://gallica.bnf.fr/ark:/12148/bpt6k3080s/f1444.image>.