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# Henri Poincaré’s life, science, and life in science

Scott A. Walter\*

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Scientific biography is a curious genre. While it shares many features with non-scientific biography, which is to say, biographies of non-scientists, the science poses a challenge, on several levels. Getting the science right is probably the most daunting of these for the biographer, all the more so when the works of the scientist in question fill eleven volumes, many being fundamental for entire branches of mathematics and mathematical physics, and some even precipitating paradigm change in physics and philosophy. Such a phenomenal scientist was Henri Poincaré (1854–1912), as shown by his intrepid biographer, Jeremy Gray.

Several reviews of Gray’s scientific biography of Poincaré have appeared, all of which emphasize what a great challenge it is to provide an adequate summary of Poincaré’s accomplishments, and how well Gray has met the challenge, even in subject areas in which he is not an expert, such as the philosophy of science.<sup>1</sup> I agree fully with the latter assessment, and am grateful that Gray has delivered the biography of Poincaré for which scholars have been waiting for over a century. Other biographies of Poincaré will be written, and indeed, another has been published by the mathematician F. Verhulst (2012). Rather than reiterate views already expressed, or provide a chapter-by-chapter summary, my aim here is to suggest how future biographers might build upon the solid foundation for Poincaré studies that Gray has provided. To do this, I will focus on Gray’s method of analysis, and examine in detail how he deals with Poincaré’s contribution to the theory of relativity.

The aim of Poincaré’s biographer, in his own words, is to “reilluminate the radiating centers of [Poincaré’s] own system of ideas” (p. 17). What this

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<sup>1</sup>Darrigol (2013), Dunlop (2014), Hentschel (2013), Sauer (2014), Stillwell (2014), Stump (2016).

lofty goal boils down to is the identification of key mathematical tools and techniques to which Poincaré returned again and again, a prime example being the Kronecker characteristic as applied to the three-body problem as well as the study of equilibrium figures arising from rotating fluid masses. As a leading expert on differential equations and group theory in the late nineteenth century, Gray offers an excellent historical analysis of Poincaré's mathematics. Reading Poincaré's original papers can be frustrating even for a trained mathematician, as he tended not to bother with formal proofs or consistent notation. This highly informal style, combined with a habit of not rereading his own papers, produced texts that challenged the understanding of his contemporaries, and continue to challenge readers today. Gray's commentary aims to render these texts accessible to students of mathematics, and will likely succeed in doing so.

At the same time, Gray provides a balanced and subtle presentation of Poincaré's philosophy of science, the topic that both opens and closes his biography. From this ordering alone, one might hastily conclude that Poincaré's philosophy is meant to provide the key to his scientific contributions. On the contrary, Gray is not concerned with teasing out the links between Poincaré's philosophy and either his approach or contributions to science.

An example of this is found in the third chapter, devoted to a prize competition in 1879–1880. Motivated by the prestigious *Grand prix des sciences mathématiques* vetted by the geometry section of the Paris Academy of Sciences, Poincaré discovered a new class of functions, that he named Fuchsian functions, and that were later referred to as automorphic functions. His path of discovery was obviously of some importance to him, and his discovery account, delivered twenty-eight years after the fact, has become both a set-piece of creative thinking, and a staple of the extensive literature of introspection, participant history, and self-fashioning. In Gray's able hands, Poincaré's account serves to illuminate the discovery of Fuchsian functions. Drawing on the edition of Poincaré's three supplements to the memoir submitted for the *Grand prix* (Gray & Walter 1997), and his monograph on the history of linear differential equations and group theory (2000), Gray correlates the episodes of Poincaré's discovery account with Poincaré's contemporary writings, and his correspondence with Lazarus Fuchs and Felix Klein. It was Poincaré's discovery of Fuchsian functions, Gray comments, that "made his name among mathematicians everywhere" (p. 246).

A major episode of this discovery, and perhaps even the key episode, was the one Poincaré described in the essay mentioned above, on mathematical invention. One spring day in 1880, while boarding a carriage leaving the coastal town of Coutances, Poincaré hit upon a novel idea: that the geometric figures he had been contemplating were equivalent, via a transfor-

mation, to figures appearing in Beltrami's disk model of hyperbolic geometry. Equipped with this insight, Poincaré could easily analyze the periodicity of the new functions he had discovered; doing so, as C. Houzel (1991) has observed, effectively changed non-Euclidean geometry from a logical curiosity to a standard tool of mathematics. At least one commentator, Élie Zahar (1997) has argued that Poincaré's geometric conventionalism had its origins in his discovery of Fuchsian functions. And while Gray notes, in the first chapter, that Poincaré's philosophical essays on non-Euclidean geometry employed the same type of model of hyperbolic geometry as the one he invented in 1880, he neither claims nor suggests that Poincaré's geometric conventionalism issued from his discovery of Fuchsian functions, or vice-versa.

Before Gray, no historian had succeeded in publishing a comprehensive account of the accomplishments of this famous French polymath. In this respect, Poincaré has fared much worse than his younger contemporary Albert Einstein, whose life continues to attract the attention of general biographers, and not just the small subset of professional historians of science. Modern biographers of Einstein tend to portray a "humanized" image of the protean physicist, i.e., one who was a womanizer, had gastric trouble, and who made mistakes. There is at least one Einstein biography that prides itself on being a compendium of blunders of one sort or another.

Poincaré looked favorably on women in science, had prostate trouble, and made blunders. Gray recalls in detail the most famous of these, having to do with the analysis of solutions near a periodic solution in the restricted three-body problem. The analysis in question was part of a long memoir submitted for the prize offered by King Oscar II of Sweden in 1889, to be awarded by a jury composed of Weierstrass, Hermite, and Mittag-Leffler. None of these mathematicians detected Poincaré's error, which had serious consequences for Poincaré's argument. Nonetheless, the jury, Gray tells us, "can be forgiven" for not noticing the error in a memoir acknowledged to be incomplete (p. 277). It was during the post-award process of preparing explanatory notes for publication that Poincaré realized his blunder; while correcting it, Poincaré discovered "doubly-asymptotic" trajectories, of the sort encountered in chaos theory (p. 273). The account Gray provides of Poincaré's mistake, and how it led him to one of his most celebrated discoveries, is a true gem of historical writing, as it takes us behind the scenes, and allows us to see how complex and fragile the business of opening the frontiers of knowledge can be.

Only a handful of Poincaré's contemporaries were ever aware of his mistake. First described by Barrow-Green (1994) and Andersson (1994), Poincaré's error – and his remarkable recovery – rapidly entered the working history of mathematicians. Since the 1960s, another blunder of Poincaré's has entered

into a working history, this time in physics: that of having preferred Galilei spacetime to Minkowski spacetime. The chief difference here, is that the nature of Poincaré’s mistake is generally considered to be philosophical rather than technical. Given the vast extent of the literature on the thorny topic of Poincaré and relativity, Gray could hardly avoid taking it up in his biography.

In this circle of ideas, Gray’s biography has a significant predecessor, namely Peter Galison’s controversial monograph *Einstein’s Clocks and Poincaré’s Maps: Empires of Time*, published a decade earlier (Galison 2003). Galison’s book compares the parallel paths to relativity of his two protagonists, in an ambitious effort to overturn half a century of scholarship on the origins of Einstein’s theory of relativity, by situating these origins in the “material culture” of early-20th-century clock-synchronization technologies and their imbrication in local and global economies. While Galison’s scholarship on Einstein attracted close scrutiny (Martinez 2004), his novel account of Poincaré’s path to relativity effectively draws on the Frenchman’s scientific and personal correspondence, and on archival records of his activity as a member (and occasional president) of the Paris Bureau of Longitudes. With the help of these documents, Galison portrays Poincaré’s scientific personality as formed in the shadow of France’s defeat in the war of 1870–1871 and disciplined by the *École polytechnique* and the *École des mines*, where Poincaré was a star student from 1873 to 1878. It was a Third-Republic scientist-engineer, Galison argues, who applied “analytical reason as readily to the understanding of a coal-mine accident as to planetary motion, as easily to the mapping of the world as to the reconstruction of Lorentz’s theory of moving electrons” (p. 305).

Gray, like Galison, is keen to explain Poincaré’s role in discovering the theory of relativity, but unlike the Harvard historian of physics, he has little to say about Poincaré’s non-public persona or his non-scientific correspondence; nor does he delve deeply into what Poincaré accomplished during the twenty-five years he spent at the helm of France’s two major scientific institutions: the Bureau of Longitudes and the Academy of Sciences.

Instead, this biography is limited to what Gray calls Poincaré’s “public life” (p. 2). His unstated postulate seems to be that Poincaré’s day-to-day life had little, if anything, to do with his science. From this it follows that an adequate understanding of one of the most highly-celebrated mathematicians of all time can be obtained by focusing on a selection of his published works, and by comparing these to those of his peers. These general differences toward intellectual biography help explain why the approaches of Galison and Gray toward understanding Poincaré’s path to relativity are diametrically opposed. Nor should it surprise us to find that their assessments of Poincaré’s contributions to relativity diverge.

The decision to ignore the minutiae of Poincaré’s day-to-day existence in favor of an account of the printed product of his fertile imagination significantly reduced the bulk of Gray’s book, which still weighs in at close to six hundred pages. The sheer volume of Poincaré’s published output, combined with the breadth of its purview – across pure and applied mathematics, celestial mechanics, cosmogony, physics, technology, and philosophy – clearly requires an organizing principle and a pruning device.

For the former, Gray was inspired by the subject of his biography. In response to a request from his friend and ally, the Swedish mathematician Gösta Mittag-Leffler, Poincaré assigned his extant publications in 1901 to seven sections, identified the most important contributions, and explained their interconnections.<sup>2</sup> The seven sections are as follows: 1) differential equations; 2) theory of functions; 3) questions in pure mathematics; 4) celestial mechanics; 5) mathematical physics; 6) philosophy of science; 7) varia. In turn, Gray divides his biography into eleven chapters (plus an appendix), including all of Poincaré’s sections (where the varia correspond to chapter 2, “The essayist”), complemented by a short chapter on cosmogony, which Poincaré had not yet explored in 1901, a second chapter on topology (subsumed by Poincaré under pure mathematics), a third on the three-body problem (subsumed by Poincaré under celestial mechanics), and a fourth on the prize competition of 1880 (corresponding to Poincaré’s section on differential equations).

A significant barrier for Poincaré studies, at least for anglophone readers, is the fact that Poincaré almost always wrote in French. While Poincaré’s philosophical books have all been translated to English, the translations are of uneven quality, and Gray sensibly provides his own rendering when this is called for. The only translation error I noticed was in the expression of the second law of thermodynamics, which Gray quotes Poincaré as stating “that heat cannot pass from a colder body to a hotter one” (p. 514). One word can make a difference: what Clausius actually claimed, and what Poincaré affirmed in turn, was that heat *by itself* cannot pass from a cold body to a hot one: “La chaleur ne peut passer d’elle-même d’un corps froid sur un corps chaud” (Poincaré 1892b, 114).

Physical phenomena fascinated Poincaré throughout his career, and as professor of mathematical physics at the Sorbonne (from 1886 to 1896), he had the occasion to lecture on the subject from all sides. His approach to physics is well documented, thanks largely to student note-takers, with whose help Poincaré published fourteen volumes of lectures by 1902, not counting his *Méthodes nouvelles de la mécanique céleste*, in three volumes

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<sup>2</sup>Mittag-Leffler to Poincaré, 1900-10-15, Walter (2016, Doc. 1-1-164); Poincaré (1921).

(1892–1899). Of these fourteen volumes, Gray selects four for commentary, covering cosmogony, electrodynamics and relativity, thermodynamics, and probability.

When Poincaré began his career, the leading lights of physics were active in Great Britain, Germany and Austria, but not France. J.C. Maxwell, William Thomson (Lord Kelvin), Rudolf Clausius, Ludwig Boltzmann, and Gustav Kirchhoff ushered in a new era of physics, characterized by the fields of thermodynamics, Maxwellian electrodynamics, and kinetic gas theory. The mathematical development of these sciences opened up a new sub-discipline – theoretical physics – which fascinated the young Poincaré and absorbed much of his attention from the time of his accession to the chair of mathematical physics and probability calculus, vacated by Gabriel Lippmann at the Paris Faculty of Sciences in 1886.

Over the next decade, Poincaré published eleven of his fourteen volumes of mathematical physics, while making major advances in systems dynamics, partial differential equations, and algebraic topology. Poincaré’s lecture style was lauded for its elegance; he proceeded in general from a few carefully-chosen experiments, from which he extracted a mathematical representation to serve as the basis for further formal development. The more mathematically inclined physicists took delight in this approach, although some, like P. G. Tait (1892), felt Poincaré relied too much on his mathematical talents, at the expense of an understanding of physical phenomena thoroughly grounded in experiment. Tait’s criticism had no discernible effect on Poincaré’s teaching style, which was much emulated in the 20th century, and which actually paid greater attention to experimental results than, say, the lectures of Arnold Sommerfeld, or those of Sommerfeld’s former student, Wolfgang Pauli. Unlike the latter physicists, Poincaré created no school in physics. His contemporary Arthur Korn (1912), however, commented that one could not find a physicist anywhere who had not been stimulated, directly or indirectly, by his lectures on mathematical physics.

Further evidence of Poincaré’s impact on early-20th-century physics is provided by the fact that he was frequently considered – but always passed over – for the Nobel Prize in physics. To explain why the Royal Swedish Academy of Sciences (RSAS) decided to award the 1910 prize in physics to J. D. van der Waals instead of Poincaré, Gray notes the frank opposition to the Frenchman’s candidacy from previous winners J. J. Thomson and Ernest Rutherford, and the lukewarm support from the 1902 winners Pieter Zeeman and H. A. Lorentz. “Should Poincaré have received the prize?” Gray asks (p. 198). There are certainly instances where such a question may be sensibly posed. The Swiss theorist Walter Ritz, to give one example, was overlooked for the Vaillant Prize of the Paris Academy of Sciences in

1907, because Poincaré misunderstood a key argument of his memoir. When Poincaré realized his error, he took steps to repair the damage (Pont 2012). In the case of the 1910 Nobel prize, by contrast, no one pretends that the nominators or the members of the RSAS were mistaken when they preferred Van der Waals over Poincaré.

Beyond second-guessing the 1910 physics Nobel committee, Gray seeks to assess Poincaré’s stature as a physicist. Like many previous commentators, he recalls Louis de Broglie’s remark to the effect that Poincaré was “more an analyst than a physicist” (p. 199). I imagine that if the context of de Broglie’s remark were better known, it would be repeated less frequently. When Prince de Broglie made this remark in 1954, he was the Perpetual Secretary for mathematical sciences at the Paris Academy of Sciences, and his leadership of French theoretical physics had been roundly criticized by the Göttingen-educated MIT physicist V.F. Weisskopf, who observed it in action while a Fulbright Scholar at the Paris Faculty of Sciences during the 1950–1951 school year. Weisskopf wrote in *Physics Today* (1951) that the research performed by the groups led by de Broglie and Proca at the Henri Poincaré Institute was “of a rather abstract character and perhaps too much of the formal mathematical type.” His critique was later echoed by *La nouvelle critique*, a French-Communist-Party-edited Parisian periodical, where one read how the “French school of theoretical physics assembled around L. de Broglie” was marked by its “preference for the formal and mathematical sides of theories of physics.” The Henri Poincaré Institute was further described as “long laboring without any contact with experiment, even feeding a certain scorn for experiment . . .”.<sup>3</sup> Such criticism was effectively countered by casting France’s most prolific theoretical physicist as essentially an analyst. In any case, asking Louis de Broglie to characterize Poincaré’s standing among 20th-century physicists is much akin to asking a sitting President of the United States of America to describe the accomplishments of his predecessors: what would one expect him to say? Putting questions of politics aside, it is unclear whether Gray fully agrees with de Broglie’s assessment, since he describes Poincaré at one point as more an applied mathematician than an analyst (p. 311).

In 1908, when Poincaré came to see himself as a candidate for the Nobel Prize in physics, he drew up a shortlist of his principal contributions in this domain for the benefit of Gaston Darboux, his former thesis advisor, and the Paris Academy’s Perpetual Secretary for mathematical sciences. Darboux

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<sup>3</sup>Jean-Pierre Joyeux, A propos de la lutte idéologique en Physique, *La nouvelle critique* 76, 1956, cited by Vila Valls (2012, 196), my translation. Vila Valls notes the criticism of the dominant interpretation of quantum mechanics, later known as the “Copenhagen Interpretation”, emanating circa 1950 from Soviet physicists and philosophers.



had suggested that he build his candidacy on the strength of what was later known as the Poincaré recurrence theorem, but Poincaré had other ideas, to wit: his contribution to the theory of partial differential equations (1890), and his theory of polarization by diffraction (Poincaré 1892a, 1897, Walter 2016, § 2-62-18). The recommendation that Darboux sent to the Nobel committee (co-signed by Paul Appell and Ivar Fredholm) followed Poincaré’s suggestion to put forward Poincaré’s contributions to the theory of partial differential equations of mathematical physics, while it demoted the theory of polarization by diffraction. In place of the latter theory, Darboux promoted Poincaré’s contributions to the theory of relativity.

Gray treats both of these topics, although not in connection with Poincaré’s bid for the Nobel prize in physics. The first topic comes up in chapter seven, on the “Theory of functions and mathematical physics”, and follows Jean Mawhin’s authoritative account (Mawhin 2010). This concerns Poincaré’s famous “*méthode de balayage*” or sweeping-out method for solving the Dirichlet problem. Gray notes that this approach was soon to be eclipsed, first by Fredholm’s work on integral equations in 1899, then by that of Hilbert and his students, beginning in 1904. Hilbert and Poincaré both profited from Fredholm’s insight, but since Hilbert and his entourage survived WWI, they developed the theory and wrote the textbooks, in which they tended to downplay Poincaré’s achievements.

The history of the theory of integral equations is complex. Gray sorts it out in perspectivist style, first by recalling Dieudonné’s reconstruction (1981) of Fredholm’s discovery, noting next Hilbert’s focus on symmetric kernels, which led him, along with his student Erhard Schmidt, to develop a powerful theory of operators on infinite-dimensional vector spaces, thereby subsuming the theory of integral equations. Poincaré took up Fredholm’s theory in 1908, and when Hilbert invited him to deliver the first Wolfskehl lectures in Göttingen, Gray tells us how Poincaré used this opportunity to present his work-in-progress. In his Wolfskehl lectures on Fredholm’s equation, Poincaré mentions how Hilbert had improved upon Fredholm’s theory of integral equations. He later gave a similarly modest appraisal in his report on Hilbert’s career achievements for the 1910 Bolyai prize, a prize awarded to Poincaré five years earlier. Gray sees Poincaré’s assessments of Hilbert’s work on symmetric kernels as ungenerous, and chalks them up to professional rivalry.

The content of all six of Poincaré’s Wolfskehl lectures, sketched briefly by Gray, suggests that he probably had the Nobel prize on his mind.<sup>4</sup> Following path-breaking work by Ze-neck and Sommerfeld, Poincaré deployed Fred-

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<sup>4</sup>For details on Poincaré’s Wolfskehl lectures, see Rowe (2017) and Walter (2017b).

holm's theory in search of a theory of long-distance propagation of Hertzian waves (Yeang 2013). The need for a new theory of propagation of Hertzian waves was particularly pressing, since Marconi and others had succeeded in transmitting wireless waves across the Atlantic, a feat that contradicted theoretical expectations. The Strasbourg physicist Ferdinand Braun shared the Nobel Prize in physics with Marconi in 1909 for accomplishments in wireless technology, a fact likely to have given pause to Poincaré when deciding which of his own papers to put forward in his bid for the prize the following year. In addition, Poincaré had nominated Augusto Righi for the Nobel prize in 1905 for his work on Hertzian waves, and Marconi backed Poincaré for the prize in 1910.<sup>5</sup>

Poincaré concluded his Wolfskehl lecture on the topic of Hertzian wave propagation with the observation that intercontinental wireless telegraphy was not ruled out by his mathematical analysis. One imagines that his Göttingen audience let out a collective sigh of relief at this point. However, after returning to Paris, Poincaré realized that his original analysis was faulty; the correct conclusion should have shown that long-distance telegraphy was impossible! For the publication of his lectures, instead of correcting the error, Poincaré appended a short note in French, alerting readers to his mistake (Poincaré 1910b).

In addition to wireless telegraphy, Poincaré spoke in Göttingen about another revolutionary topic (hence potentially relevant for a Nobel prize): the theory of relativity. Hilbert's colleague Hermann Minkowski, whom he described to Poincaré as being a friend "a thousand times more like a brother", had died suddenly, less than two months after Poincaré accepted Hilbert's invitation.<sup>6</sup> Minkowski's lecture "Raum und Zeit", which presents the Göttingen mathematician's spacetime theory for the general reader, and marks a turning point for the reception of Einstein's theory of relativity, was published in February, 1909. Although Minkowski's lecture makes no mention of Poincaré, Minkowski's spacetime theory borrowed key formal insights from Poincaré's memoir on electron dynamics (1906).

There was some question in 1909 as to where on the global map spacetime theory should be located. Was it born in Göttingen, where two years earlier, Minkowski conceived of, presented, and furthered a research program in the physics of worldlines in spacetime? Or did it first arise in Paris, where Poincaré showed that the Lorentz transformations form a group that may be interpreted geometrically as a rotation about the origin in a four-dimensional

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<sup>5</sup>See Poincaré to the Nobel Committee for Physics, 24 January, 1905, and Marconi to the Nobel Committee for Physics, 13 January, 1910, both in Walter (2016).

<sup>6</sup>Hilbert to Poincaré, 25 February, 1909, in Walter (2016).

vector space with one imaginary axis? As mentioned above, the case for Paris was furthered by Darboux’s letter of nomination of Poincaré for the 1910 Nobel Prize, which prominently cited the principle of relativity among Poincaré’s major contributions to physics. During his stay in Göttingen, Poincaré conceded nothing at all to the late Minkowski on this count. Rather, he underlined the Gallic origins of relativity by switching from German to French for the delivery of the last of his six Wolfskehl lectures, entitled “la mécanique nouvelle”.

Gray’s biography provides a summary of the latter lecture, along with an extended account of Poincaré’s contributions to relativity. His story begins with the rise of electron theory in the 1890s, and what Gray terms Poincaré’s “public disenchantment” with Fresnelian optics (p. 337). Privately, in his recommendation for the Nobel Prize in physics for 1905, Poincaré lauded Augusto Righi for having verified Fresnel’s law of reflection and refraction for electric rays, by producing 26-millimeter electromagnetic waves (later called microwaves).<sup>7</sup> One law Righi neglected to test was that of Fresnel drag. Devised by Augustin Fresnel in 1818 as a means of explaining Arago’s prism experiment, Fresnel drag is expressed as a sum of velocities,

$$V = c/n + (1 - 1/n^2)U,$$

where  $V$  is the propagation velocity of light through a transparent body of velocity  $U$  with respect to the still ether. When the body is at rest with respect to the ether, we have  $U = 0$ , and the propagation velocity of light through the body  $V$  is just the velocity of light through matter-free ether  $c$  divided by the refractive index  $n$  of the body at rest:  $V = c/n$ . In mid-century, Hippolyte Fizeau found the propagation velocity of light in flowing water to increase with flow velocity, just as predicted by Fresnel’s drag formula.

For many years, Fizeau’s confirmation of Fresnel drag held sway among physicists, but there was a problem. Fresnel had supposed the ether to be at absolute rest in regions of space free of matter, and that transparent bodies in motion dragged a bit of ether along with them. This supposition had to be discarded when Élie Mascart showed via double-refraction experiments that Fresnel’s drag coefficient depends on wavelength (Darrigol 2000, 316). Lorentz then provided a new justification for Fresnel drag, in part by positing that matter in motion did not drag the ether at all. Instead, Lorentz posited charged particles (of which matter was comprised in this model) that interact via a stationary ether according to microscopic Maxwell-Hertz field equations, each particle being subject to a force, later known as the Lorentz force, the magnitude of which depends on charge density, field intensity, and

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<sup>7</sup>Poincaré to the Nobel Committee, 24 January 1905, Walter (2016, Doc. 2-62-12).

particle velocity. Lorentz showed that his equations lead to the Fresnel drag, by introducing a curious set of transformations that leave the wave operator invariant, including a transformation of the time coordinate,  $t' = t - \mathbf{v}\mathbf{x}/c^2$ , which he would later call *Ortszeit* (Lorentz 1895).

Lorentz's interpretation of Fresnel drag in terms of microscopic charged particles (soon identified as "electrons") was a surprising, and much-remarked result. In France, Poincaré's former student Alfred Liénard reviewed Lorentz's theory, and in doing so, translated Lorentz's *Ortszeit* as *temps local*, or local time (Liénard 1898, 321). In 1900, Poincaré established local time as a physical quantity (to first order in velocity over the propagation velocity of light in vacuum,  $v/c$ ), by defining it operationally: local time is indicated by an ideal clock in inertial motion, provided that the clock is optically synchronized with identical co-moving clocks, with correction for signal time-of-flight at rest, but no correction for motion with respect to the ether.

Up to this point in the history of electrodynamics, all commentators are agreed on the essentials. Where Galison and Gray part ways, is over what happened next, and why. For Galison, Poincaré's theory of relativity is best understood as issuing from his "engaged mechanics", where the "material and the abstract shaped one another" (p. 308). The meeting place for the material and the abstract was Leiden, where Lorentz's colleagues organized a meeting to celebrate the jubilee of his doctoral defense, on 11 December, 1900. Poincaré did not attend, but he contributed a paper on Lorentz's electron theory that provided an operational definition of Lorentz's local time, as mentioned above.

This particular definition can be linked to Poincaré's conventionalist philosophy; at the same time, it was tied to his scientific oversight, via the Bureau of Longitudes and the Academy of Sciences, of a project to measure an arc of meridian running through Peru, Ecuador, and Columbia. Notably, Poincaré observed as early as 1898 the conventional nature of distant simultaneity, and that the synchronization of clocks by telegraphic signals represented one of several ways of coordinating clocks, and thereby, of defining time. In a nutshell, this is Galison's triad: metaphysics, physics, technology. Poincaré's theory of relativity would spring from all three, while expressing the pragmatic, forward-looking worldview of a Third-Republic Polytechnician.

Gray's version of Poincaré's theory of relativity is a much simpler affair than that of Galison. It has nothing to do with philosophical reflection on the meaning of time and simultaneity, or swashbuckling episodes of longitude measurement in Quito, although Gray addresses each of these topics in its own right. Instead, he develops a detailed account of the genesis of relativity beginning with the mid-19th-century theories of electricity of Maxwell and

Helmholtz, which draws on studies by Olivier Darrigol, Jed Buchwald, and Arthur Miller. For Gray, Poincaré’s “inspired discovery” is not the operational definition of local time (as Galison has it), but the fact that the Lorentz transformations form a group (p. 373).

Lorentz himself had not recognized the latter fact, any more than he had imagined that *Ortszeit* could be construed as a measurable quantity. How important was this discovery? Galison passes over in silence both Poincaré’s and Einstein’s discovery of the Lorentz group, perhaps because being mathematical, it does not fit into his triad. Hermann Minkowski famously exploited the properties of the Lorentz group in his theory of spacetime (1908). But prior to Minkowski’s contribution, what was Poincaré’s understanding of the physical meaning of the Lorentz group?

Or Einstein’s, for that matter. Gray notices the remark, in a footnote to Einstein’s article of 1905, that the rather long-winded kinematic derivation of the Lorentz transformations could be shortened by invoking form-invariance of the equation of a spherical lightwave (p. 376). As McCausland pointed out, the footnote in question did not appear in the original publication of 1905, but was added when Otto Blumenthal published a collection of original articles on relativity in 1913.<sup>8</sup> The short derivation of the Lorentz transformations alluded to in the 1913 footnote is due to a remark made in October, 1907, by the 1902 Senior Wrangler Ebenezer Cunningham.<sup>9</sup>

From a modern standpoint, the covariance of the laws of physics with respect to the transformations of the Poincaré group (of which the Lorentz group is a subgroup) expresses the isometries of Minkowski spacetime, and the content of the special theory of relativity. This was not so for Einstein in 1905, as we have just seen. Neither was it so for Poincaré, who was initially at pains to admit the reality of time dilation. According to Gray’s rational reconstruction, however, Poincaré would have expounded the notion of relativistic time dilation in lectures delivered at the Paris Faculty of Sciences in 1906–1907 (p. 376).

Gray’s argument in favor of Poincaré’s acceptance of time dilation in 1906–1907 is succinct, and runs as follows. Poincaré defined a measurement protocol whereby a unit of length is defined by light time-of-flight. Poincaré then argued, according to Gray, that “a moving and a stationary observer will agree on the shape of a spherical wave front, because the Lorentz contraction of length is exactly compensated for by a dilation in time . . .” (p. 376).

Gray’s reconstruction is based on the edition of student lecture notes

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<sup>8</sup>See McCausland (1984), Blumenthal (1913), and Stachel (1989, Doc. 23, note 8).

<sup>9</sup>Goldberg (1970), Cunningham (1907). Cunningham’s remark represents the first contribution to relativity theory from a British scientist; for details, see Walter (2017a).

published by the Bordeaux astronomer Marguerite Chopinet in 1953. My own study of the original manuscripts reveals, instead of time dilation, only a recapitulation of Poincaré’s operational (first-order) definition of local time, mentioned above, along with the following comment on Lorentz contraction and clock synchronization, which was suppressed in the 1953 edition:<sup>10</sup>

So Lorentz assumes that all bodies undergo a contraction in the direction of motion proportional to the square of velocity. Lengths are then altered, and durations are altered by the impossibility of setting watches truly, such that the apparent velocity of light is constant. Then we perform a Lorentz transformation: the Lorentz transformations must form a group, such that we have identically

$$x^2 + y^2 + z^2 - t^2 = x'^2 + y'^2 + z'^2 - t'^2.$$

What Poincaré taught his students in 1906–1907, or more precisely, what one of these students noted at the time, was that clocks in motion cannot be set properly. This view of clocks in motion is consistent with Poincaré’s earlier operational definition of local time (mentioned above), according to which light-synchronized clocks in uniform motion are reliable to first order in  $v/c$ .

In his original contribution to relativity (1906), Poincaré had no compelling reason to take up clock synchronization, since he employed an active Lorentz transformation, instead of the passive transformation preferred by Lorentz, Einstein, and most physicists ever since (Sternberg 1986, 69). But in lectures to university students, and when writing for a general audience, Poincaré felt the need to explain the passive Lorentz transformation. To do so, he resorted to a thought-experiment involving flying rods and stationary clocks, which a stationary observer used to measure the shape of a light-pulse. The apparent shape of a light-pulse (for any nonzero rod velocity), Poincaré maintained, would always be an ellipsoid of rotation, elongated in the direction of rod motion, and with a focus located at the light source. His interpretation, while consistent mathematically, was physically flawed. By the time of his Wolfskehl lectures in April, 1909, Poincaré must have

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<sup>10</sup>“Donc Lorentz suppose que tous les corps subissent dans la direction du mouvement une contraction proport. au carré de la vitesse. Alors les longueurs sont altérées, & les temps sont altérés par l’impossibilité de régler vraiment les montres. Ce qui fait que la vitesse apparente de la lumière est constante. Alors nous effectuons une transformation de Lorentz : les transfor. de Lorentz doivent former un groupe, tel que l’on ait identiquement  $x^2 + y^2 + z^2 - t^2 = x'^2 + y'^2 + z'^2 - t'^2$ .” Henri Vergne, notebook 2, 52, François Viète Center.

seen the flaw, since he then allowed for clocks in motion and time deformation, thereby discreetly bringing his theory in line with those of Einstein and Minkowski.<sup>11</sup>

In all likelihood, Poincaré's adoption of time deformation in Göttingen engaged, at least in part, with Minkowski's spacetime theory of physics (1908). Along with physics, another element of Galison's triad was certainly at work here: technology. When Poincaré discussed time deformation, his thought-experiment employed two observers in relative motion, who exchange time-stamped position data wirelessly. Upon tabulating the telemetry data, each observer comes to the inevitable conclusion that her on-board clock runs at a rate unequal to that of the clock located in the other vehicle (Poincaré 1910a).

What is most striking about the Göttingen telemetry episode is Poincaré's seemingly effortless intertwining of philosophy, mathematics, physics, and electrotechnology. To try to capture Poincaré's theory of relativity from the standpoint of any one of these disciplines is not wrong, but incomplete, and in the end, intellectually unsatisfying. Likewise, for the adequacy of a strict disciplinary approach to understanding Poincaré's life in science: the gist of his contributions may be captured, but his path of discovery is likely to escape us.

To return to the broad topic of scientific biography, Gray's life of Poincaré may be taken as a working example. Gray provides a scholarly, readable, and reliable account of Poincaré's discoveries, how Poincaré understood what he discovered, and how his discoveries fit in the broader scheme of knowledge. This is a singular accomplishment, which will benefit Poincaré studies for years to come. However, by dividing his biography into chapters covering the fields and disciplines in which Poincaré labored, Gray shunts cross-field and cross-disciplinary elements to the background. Poincaré's cross-disciplinary endeavors set him apart from his mathematical peers, and I imagine that future Poincaré biographers will want to foreground Poincaré the polymath, instead of Poincaré the essayist, mathematician, physicist, or philosopher. Similarly, the relegation of Poincaré's private life and career to a single chapter tends to obscure the embedding of Poincaré's science in the extraordinarily rich cultural and institutional setting of Belle Epoque Paris. In summary, while Gray's scientific biography of Poincaré does not renew the genre, it provides a solid foundation for those wishing to explore the finer details of Poincaré's life in science.

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<sup>11</sup>Poincaré's diagrammatic interpretation of the Lorentz transformations prior to 1909 shows that an observer at rest with respect to the ether can receive light signals from spatial locations at distances greater than those corresponding to light time-of-flight. For details, see Walter (2014).

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