Introduction

WARNING: THIS DISSERTATION IS WRITTEN IN INFORMAL LANGUAGE.
PHILOSOPHERS ENTER THIS DOCUMENT AT THEIR OWN RISK.[1]

In this dissertation, I want to compare the ether theory of the great Dutch physicist Hendrik Antoon Lorentz (1853–1928) to Einstein's special theory of relativity. To the end of his life, Lorentz maintained, first, that his theory is empirically equivalent to special relativity, and, second, that, in the final analysis, it is a matter of taste whether one prefers the standard relativistic interpretation of the formalism of the theory or his own ether theoretic interpretation (see, e.g., Nersessian 1984, pp. 113–119). I will argue that Lorentz's first claim, when understood properly, should be accepted, but that the second should be rejected.

Lorentz's theory and special relativity have, of course, been compared numerous times before (see, e.g., Goldberg 1969, 1984; Hirosige 1968, 1976; Holton 1969; McCormmach 1970a; Miller 1981, 1986; Nersessian 1986; Pais 1982; Schaffner 1969, 1970, 1974, 1976; Zahar 1973, 1989). As a rule, the format for such comparisons is a detailed study of the development of Lorentz's theory for the electrodynamics of moving bodies from the 1890s to the 1910s, with some comments at the end as to why the author thinks that the final version of this theory is less attractive than special relativity. My comparison of the two theories in part two of this dissertation will be no exception to this rule. In chapter three, I will give a lengthy

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[1] The point Rilke once made about poets in one of my favorite passages in German literature applies equally well, I think, to philosophers of science: "Ich begreife übrigens jetzt gut, daß man ganz innen in der Brieftasche die Beschreibung einer Sterbestunde bei sich trägt durch alle die Jahre. Es müßte nicht einmal eine besonders gesuchte sein; sie haben alle etwas fast Seltenes. Kann man sich zum Beispiel nicht jemanden vorstellen, der sich abschreibt, wie Felix Anvers gestorben ist. Es war im Hospital. Er starb auf eine sanfte und gelassene Weise, und die Nonne meinte vielleicht, daß er damit schon weiter sei, als er in Wirklichkeit war. Sie rief ganz laut irgend eine Weisung hinaus, wo das und das zu finden wäre. Es war eine ziemlich ungebildete Nonne; sie hatte das Wort Korridor, das im Augenblick nicht zu vermeiden war, nie geschrieben gesehen; so konnte es geschehen, daß sie ›Kollidor‹ sagte in der Meinung es hieße so. Da schob Arvers das Sterben hinaus. Es schien ihm nötig, dieses erst aufzuklären. Er wurde ganz klar und und setzte ihr auseinander, daß es ›Korridor‹ hieße. Dann starb er. Er war ein Dichter und hasste das Ungefähre" (Rilke 1910, pp. 133–134). ["Moreover I now understood very well how one could carry with one, through all the years, deep in one's portfolio, the description of a dying hour. It need not even be an especially selected one; they all possess something almost rare. Can one not, for example, imagine somebody copying out the description of Felix Arvers' death? It took place in a hospital. He was dying with ease and tranquillity, and the sister, perhaps, thought he had gone further with it than he really had. In a very loud voice she called out an order, indicating where such and such was to be found. She was hardly an educated nun, and had never seen written the word 'corridor,' which at the moment she could not avoid using; thus it happened that she said 'collidor,' thinking it ought to be pronounced so. At that Arvers thrust death from him. He felt it necessary to put this right first. He became perfectly lucid and explained to her that it ought to be pronounced 'corridor.' Then he died. He was a poet and hated the approximate" (Rilke 1910, p. 158)]. I find it very telling (and perceptive) that Rilke talks about a poet here, not about a scientist. I invite philosophers of science to ponder the question what Einstein, Bohr, and Dirac would have done had they been in Felix Arvers' predicament.

discussion of the development of Lorentz's theory; in chapter four, I will make some brief comments explaining what I think gives special relativity the edge over Lorentz's theory. The reason I can be brief in chapter four is that the whole discussion in chapters one through three is geared toward the points I want to make in chapter four. The reason that chapter three is overly lengthy is not that the development of Lorentz's theory is all that complicated—on the contrary: it is completely straightforward—but that I have major disagreements with almost all existing accounts of this development. I will elaborate on some general historiographical issues in the introduction to part two and on the more specific factual disagreements in the introduction to chapter three. In this overall introduction, I just want to give an outline both of my understanding of the development of Lorentz's theory and of the overall argument in this dissertation.

Before 1905, Lorentz looked upon the Lorentz transformation equations as defining some auxiliary quantities that were helpful in proving that ether drift can never be detected,[2] at least not through optical experiments that eventually boil down to the observation of some pattern of light and darkness, as most optical experiments do. These proofs are based on so-called theorems of corresponding states.[3] In the case of first order experiments,[4] the proof does not require the addition of any new physical hypotheses to what in Lakatosian terms would be called the "hard core" of Lorentz's research program.[5] Lorentz's first order theorem of corresponding states of 1895 simply provides an elegant mathematical method for showing that this core theory does not predict a first order effect of ether drift on patterns of light and darkness. Lorentz's exact theorem of corresponding states of 1899–1904 shows that the core theory does predict second order effects of ether drift on patterns of light and darkness, such as the effect Michelson and Morley were looking for. The explanation of the negative results of these experiments required additional physical hypotheses. However, after Lorentz had found the exact theorem of corresponding states, he no longer simply added the contraction hypothesis he and FitzGerald had introduced earlier to account for the Michelson-Morley experiment. Instead, he added assumptions from which he could derive that the effect of ether

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[2] Even this basic claim turns out to be controversial, although I am by no means the first to set the record straight on this score (see, e.g., Rynasiewicz 1988, Darrigol 1994a).

[3] See the introduction to chapter three for a more detailed yet still non-technical explanation of the notion of corresponding states and of the theorem of corresponding states.

[4] By "first order experiments" I mean experiments measuring effects in the order of magnitude of $v/c \approx 10^{-4}$, the ratio of the velocity of the earth in its orbit around the sun (which was taken to be a good estimate of the order of magnitude of its velocity with respect to the ether) and the velocity of light in vacuo. This ratio is sometimes called the aberration constant.

[5] Roughly, this hard core consists of Newtonian mechanics (including Newtonian space-time), Maxwell's equations, the equation for the Lorentz force, and a dualistic ontology of ether and matter with ether as the sole carrier of the electromagnetic field and charged particles (first called 'ions' and later 'electrons') as the only mediators between the stationary ether and matter.

drift on the optical components producing some pattern of light and darkness would be the same as (and would therefore compensate) the effect of ether drift on such patterns themselves, the latter effect being a consequence of the core theory, as he had shown so elegantly with the help of the exact theorem of corresponding states. To be sure, the most important of these effects is the change in the dimensions of the system familiar from the original Lorentz-FitzGerald contraction hypothesis, but that is not the only effect. For instance, ether drift also has an effect (corresponding to time dilation from a modern point of view) both on the frequency of the light producing the pattern of light and darkness (an effect that can be derived from the core theory with the help of the exact theorem of corresponding states) and on the frequency of the oscillations of electrons in the light source responsible for the emission of light (an effect that can only be derived with the addition of new hypotheses). With the new hypotheses Lorentz added to his core theory, hypotheses that were suggested to him by the exact theorem of corresponding states, the theory predicted negative results for all optical ether drift experiments (both first and second order experiments) that eventually boil down to the observation of some pattern of light and darkness. The original Lorentz-FitzGerald contraction hypothesis, by comparison, could account for little, if anything, more than the Michelson-Morley experiment.

From a modern point of view, we have essentially the following situation. Lorentz's theorem of corresponding states is tantamount to the statement that the free field Maxwell equations are Lorentz invariant. By assuming that the laws governing the optical components producing some pattern of light and darkness are Lorentz invariant as well, Lorentz could show that ether drift has no effect on the outcome of optical experiments that eventually boil down to the observation of some pattern of light and darkness.[6]

After 1905, Lorentz realized that the Lorentz transformed quantities of his theorem of corresponding states are actually the quantities measured by a moving observer. Poincaré had used this physical interpretation of Lorentz's mathematical tool since around 1900, talking about it as if it were Lorentz's own interpretation (Darrigol 1994b).[7] Following Poincaré, many historians have read this interpretation into Lorentz's pre-1905 work. However, there is unequivocal textual evidence that he only adopted this interpretation, under the influence of Einstein rather than Poincaré, after 1905.

With the help of this new interpretation of the theorem of corresponding states, Lorentz's pre-1905 strategy of explaining negative results of ether drift experiments through a

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6 I have not been able to find a clear statement of this basic structure of Lorentz's theory in the extensive literature on the subject.

7 I am indebted to Adolf Grünbaum and John Stachel for urging me to look more closely at Poincaré's work than I originally intended to.

combination of deriving effects of ether drift on electromagnetic field configurations from the Lorentz invariance of Maxwell's equations and postulating similar compensating effects for the part of the system not governed by Maxwell's equations could be perfected to deal with any sort of ether drift experiment. The strategy was no longer restricted to optical experiments and a few other cases (notably electrostatics) that Lorentz had focused on before 1905.

His basic understanding of the status of Lorentz invariance, however, would never change. Whereas for Einstein, Lorentz invariance just reflected the relativistic space-time structure, Lorentz thought of Lorentz invariance as something that, in the case electromagnetic phenomena, could be derived from Maxwell's equations and that, in the case of non-electromagnetic phenomena, either had to be postulated or had to be derived from other more specific assumptions about the effects of ether drift on physical phenomena. In other words, Lorentz thought of Lorentz invariance as a property of the dynamical laws governing systems in a Newtonian space-time.

In this context, it is important to emphasize that, whatever his attitude toward the electromagnetic view of nature[8] may have been earlier, Lorentz had clearly broken with this tradition by 1906. Shortly after Lorentz had proposed his purely electromagnetic model of the electron (Lorentz 1904b), Abraham and Poincaré showed that the model was inconsistent. The inconsistency could be removed in two ways, either by following a suggestion by Poincaré and adding a piece of non-electromagnetic origin to the model, or by adopting Abraham's alternative purely electromagnetic electron model and sacrificing the general prediction of negative results in optical ether drift experiments involving no more than the observation of a pattern of light and darkness. I will argue in chapter three that Lorentz unambiguously opted for the former alternative. The famous experiments by Kaufmann and others on the velocity dependence of the mass of high-speed electrons in β-radiation, recently discovered by Becquerel, were meant to decide between the non-purely-electromagnetic relativistic electron model of Lorentz and Poincaré and the purely-electromagnetic non-relativistic electron models of Abraham and of Bucherer and Langevin (see chapter three). As can be gathered from an important talk by Planck in 1906, the debate over the results of these experiments was phrased in terms of the 'Lorentz-Einstein relativity postulate' versus the 'Abraham electromagnetic postulate.' This episode, I claim, clearly shows that, as early as 1906, deriving Lorentz invariance for all of physics from electrodynamics was no longer a live option. As a consequence, I claim, Lorentz's interpretation of Lorentz invariance is very unsatisfactory.

What is unsatisfactory about it is usually illustrated by looking at the transformation equations for the space-time coordinates. Lorentz and Einstein agree that any physical system

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[8] According to the proponents of this view, such as Abraham and Wien, all physics would ultimately be reduced to electrodynamics. The canonical source for the electromagnetic view of nature is still McCormmach 1970b.

contracts and that processes in the system slow down when it is set in motion, no matter whether the system is of an electromagnetic or of a non-electromagnetic nature.[9] However, whereas, in special relativity, such phenomena are simply part of the normal spatio-temporal behavior of systems in Minkowski space-time, Lorentz can only account for them if he makes the general assumption that the laws governing non-electromagnetic phenomena, like the laws governing electromagnetic phenomena, are Lorentz invariant and not Galilean invariant as one would expect on the basis of the Newtonian space-time structure posited by his theory. In short, the contraction and dilation effects are purely kinematical in Einstein's theory but (at least partly) dynamical in Lorentz's.

In the context of optical experiments[10] that only probe the basic space-time kinematics of special relativity, the transformation equations for the space-time coordinates are all we need. These experiments therefore fail to illustrate the full extent of what is involved in the assumption of Lorentz invariance as a symmetry of the dynamics in a Newtonian space-time. In the context of these optical experiments, it suffices to add two assumptions to the core of Lorentz's theory, viz. the Lorentz-FitzGerald contraction hypothesis and the assumption that whatever process is responsible for the emission of light slows down when the system in which the process occurs is set in motion.[11] Following Grünbaum (1973, p. 723), I will call this simplified version of Lorentz's theory, which is a perfectly acceptable model of the theory in the context of optics, "the doubly amended ether theory."[12] This simplified model already provides the key insights for the comparison between Lorentz's theory and special relativity. First, as Grünbaum (1959, 1973, 1976) has conclusively shown, the doubly amended ether theory is not *ad hoc* in the usual falsificationist sense of that term. Second, it clearly shows that, on Lorentz's understanding of Lorentz invariance as a symmetry of the dynamics in a classical Newtonian space-time, the contraction of rods and the retardation of clocks are combinations of dynamical

[9] In the case of special relativity, it does not make any difference with respect to which inertial frame a system is set in motion. In Lorentz's theory, we have to be a little more careful. The contraction of an object set in motion with respect to a frame at rest in the ether is a dynamical effect. The contraction of an object set in motion with respect to a frame that is itself moving with respect to the ether is partly a dynamical effect, partly the result of an artifact of measurement related to the fact that the moving observer will use (something equivalent to) Einstein's light signaling procedure to synchronize his clocks (see, e.g., Dorling 1968). Despite suggestions to the contrary by, for instance, Schaffner (1969, pp. 511–512) and Miller (1974, pp. 42–43), this is a complication in Lorentz's theory—a complication of which Lorentz was well aware (see, e.g., Lorentz 1922, 202–204)—and not a fatal flaw (see chapter three).

[10] Be it 19th century ones such as the Michelson-Morley experiment, or later 20th century ones such as the Kennedy-Thorndike experiment of 1932 or the Ives-Stillwell experiment of 1938 (see chapter three).

[11] Miller has repeatedly claimed (Miller 1974, p. 42; 1981, pp. 301–307) that Lorentz's theory does not give the relativistic predictions for the Doppler effect and for aberration. I will show (chapter three) that even this simplified version of Lorentz's theory gives exactly the same predictions for these effects as special relativity.

[12] The two hypotheses are usually formulated as hypotheses about rods and clocks (see, e.g., Zahar 1973, p. 216). This is somewhat unfortunate in that it might lend credence to the mistaken view that length contraction and time dilation are purely artifacts of measurement.

effects and artifacts of measurement, whereas, on Einstein's understanding of Lorentz invariance as expressing the symmetries of a relativistic Minkowskian space-time, they are purely kinematical phenomena.

These points can be amplified if Grünbaum's "doubly amended ether theory" is replaced by a more realistic model of Lorentz's theory and if we consider experiments in which more is at stake than the basic kinematics of special relativity, in short, if we consider Lorentz's theory in the context of non-optical experiments. The only non-optical experiments that have been discussed extensively in the literature so far (notably in Miller 1981) are the experiments of Kaufmann and others that I already mentioned above.

In part one of this dissertation, I will look at two other non-optical experiments, the famous Trouton-Noble experiment of 1903 and a related earlier experiment by Trouton that has largely been forgotten. Both experiments aimed at detecting the earth's presumed motion through the ether with the help of a condenser in a torsion balance. These experiments have so far received surprisingly little attention from historians of special relativity, partly, no doubt, because their analysis is far more complicated than the analysis of optical ether drift experiments.

The physics of the experiments is closely related to the physics of the electron model of Lorentz and Poincaré tested in Kaufmann's experiments. My analysis of the various accounts of the experiments of Trouton and Noble will involve the relativistic theory of stressed bodies in motion and the emergence of the relativistic understanding of the relation between energy and momentum, their transformation properties and their conservation laws. Not surprisingly, the stress-energy-momentum tensor—or energy-momentum tensor for short—will play an important role in my story.

The historical analysis is complicated by the fact that the various accounts of the experiments flatly contradict each other at some points without the authors (Larmor, Lorentz, and Laue) commenting on these contradictions. It turned out to be a highly non-trivial task to trace the origins of these discrepancies.

Fortunately, my efforts to straighten out the physics as well as the history of the experiments of Trouton and Noble proved to be extremely rewarding. Let me list what I consider to be my major findings.

First, my analysis will provide an exceptionally clear picture of the basic structure of Lorentz's theory of 1899–1904. In particular, it inspired a new account of the Michelson-Morley experiment in the context of this version of the theory that clearly illustrates the difference between the original Lorentz-FitzGerald contraction hypothesis and what I will call the *generalized contraction hypothesis*, the overarching physical assumption that needs to be added to Lorentz's exact theorem of corresponding states if his theory is to predict negative results for all ether drift experiments. This new account of the Michelson-Morley experiment in chapter three is a straightforward adaptation of my reconstruction of Larmor's account of the Trouton-Noble experiment in chapter one.

Second, I will show that the discrepancies between the various accounts of the experiments of Trouton and Noble due to Larmor, Lorentz, and Laue all have the same origin. They essentially stem from the fact that Larmor and Lorentz did not (properly) take into account that when we charge a moving condenser, we not only change its energy, but also its momentum and its mass. In this context, I will show that the Trouton experiment can, in fact, be seen as a physical realization of a famous thought experiment in which Einstein (1906) showed that the inertia of energy is a necessary and sufficient condition for the so-called center of mass theorem, which is closely related to Newton's action equals reaction principle and momentum conservation. The fate of this theorem in Lorentz's theory had been a topic of debate between Lorentz and Poincaré. The connection with the Trouton experiment was never made in this debate, but Lorentz predicted on the basis of the 1904 version of his theory that the experiment would, in effect, violate the center of mass theorem, although he was able to show that the effect was too small to be detected with the apparatus Trouton had used in 1902. Still, Lorentz's 1904 prediction differs from the strict null result predicted by relativity theory on the basis of the inertia of energy.

From this last observation, it is clear that we need at least a "triply amended ether theory" if such a theory is to be empirically fully equivalent to special relativity. We need to take over the inertia of energy in the ether theory. In fact, we need to take over all relativistic relations between such quantities as energy, mass, and momentum in the ether theory if such a theory is to be empirically and mathematically equivalent to special relativity. Lorentz, I think, was well aware of this, and, in effect, did take over these relations. As with the contraction hypothesis and the clock retardation hypothesis, this can be done without compromising the testability of the theory, i.e., it can be done without the theory becoming *ad hoc* in the falsificationist sense of that term. This should not be surprising. The hypotheses added to the theory to account for, say, the Trouton experiment will have all the excess empirical content they have in special relativity. What makes such a multiply amended ether theory unsatisfactory, intuitively, is not what is added, but what is retained and what is rendered more invisible with every emendation: Lorentz's stationary ether and Newtonian space-time.[13] This gets me to the third and, what I consider to be, most important result of my analysis of the experiments of Trouton and Noble.

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[13] Grünbaum already made this point in his discussion of the doubly amended ether theory. He writes: "T_2 [i.e., the amended theory] is derogated not because it introduced H [e.g., the contraction hypothesis or the time dilation hypothesis] but because it sought to rescue T_0 [i.e., the unamended core theory]" (Grünbaum 1976, p. 360).

I already mentioned that, as a consequence of Lorentz's interpretation of Lorentz invariance, there will be effects which, from a relativistic point of view, are purely kinematical, but which, in Lorentz's theory, are dynamical. In other words, there will be effects which, in special relativity, simply reflect the Minkowskian space-time structure, whereas, in Lorentz's theory, they reflect peculiarities of the dynamical laws governing systems in a Newtonian space-time. The two most obvious examples in this category are length contraction and time dilation. The only other effects of this kind I can think of that have explicitly been recognized as such are the Fresnel dragging effect, which, as Laue showed in 1907, is simply an instance of the relativistic addition theorem of velocities, and the velocity dependence of the electron mass which Kaufmann and others tried to measure, and which is just a consequence, as Laue essentially showed in 1911 (see chapter two), of the fact that the four-momentum of any closed system transforms as a four-vector under Lorentz transformation.[14] In chapter two, I will add one more item to this disappointingly short list.

In Lorentz's ether theoretic account of the Trouton-Noble experiment as well as in Laue's canonical relativistic account of the experiment, there are two turning couples acting on a moving charged condenser. One comes from the Coulomb forces on the plates of the condenser, the other from the non-electromagnetic forces that prevent the plates from collapsing onto one another under the influence of these Coulomb forces. As one would expect, the two turning couples exactly cancel one another, otherwise we would have a violation of the principle of relativity. Generalizing some insights of Rohrlich (1960, 1965) that form the core of his well-known analysis of the electron model of Lorentz and Poincaré, I will show that, in special relativity, these delicately balanced turning couples on a moving charged condenser are purely kinematical in the same sense that length contraction and time dilation are. I will coin the phrase *Laue effect* for this phenomenon, whose purely kinematical nature has so far gone unrecognized.

I want to say a few words about the organization of this dissertation. From what has just been said, the idea behind its division into part one and part two will hopefully be clear. Both parts are divided into two chapters. I have included fairly detailed introductions both to the two main parts and to chapters one through three, which contain a lot of technical material. The purpose of these detailed introductions is to give the reader a chance to get an overview of my arguments

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[14] The point can be made even more cleanly using an alternative definition of the four-momentum of spatially extended systems due to Rohrlich (1960, 1965) that I will examine in great detail in chapter two. Under that definition, the four-momentum of any system, open or closed, transforms as a four-vector, which makes it even clearer that this is not a property of the dynamical laws governing such systems but that it simply reflects the normal spatio-temporal behavior of systems in Minkowski space-time. In chapter two, we will also see that Laue could only prove this property for closed *static* systems, so that the purely kinematical nature of this property was still not entirely clear.

without having to work through the sometimes rather tedious derivations needed to establish my claims. This organization of the dissertation brings with it a certain amount of repetition, but only of points, I hope, that bear repeating.