# Chapter Four: Comparing Lorentz's understanding of Lorentz invariance to Einstein's

## 4.0 Introduction: putting the pieces together

In this final chapter, I want to use some of the results that I argued for at length in chapters one through three to make some more general comments on Lorentz's theory and its relation to special relativity. I have tried to keep this chapter as short and as non-technical as I could, avoiding, for instance, any use of equations (except $E = mc^2$ which is exempt whenever equations are banned). To a certain extent, I have to admit, appearances are deceptive, for I will actually presuppose some highly technical results from chapter three and, especially, chapter two. Still, I will present these results in such a way that they should be accessible without any detailed understanding of their derivation.

Given how short this chapter is and given that it is the natural culmination of the discussion in chapters one through three (see the overall introduction), there is no need for an elaborate introduction. In section 3.1, I will discuss how the generalized contraction hypothesis turns Lorentz's ether theory into a Lorentz invariant theory, thereby rendering it empirically equivalent to special relativity. In section 3.2, I will outline a 'common cause'-type argument to show that Einstein's interpretation of Lorentz invariance as a symmetry of space-time is preferable to Lorentz's interpretation of Lorentz invariance as a property accidentally shared by all physical laws governing systems in a Newtonian space-time. In section 3.3, I will argue that Einstein's presentation of the special theory of relativity, emphasizing the theory's axioms rather than its models, may have been partly responsible for Lorentz's apparent failure to appreciate what we now recognize as Einstein's crucial insight, viz. that Lorentz invariance is a space-time symmetry.

## 4.1 What price empirical equivalence of Lorentz's theory to special relativity?

**4.1.1 How to make Lorentz's theory empirically equivalent to special relativity in the context of experiments that involve more than the observation of patterns of light and darkness.** As will be clear from the discussion in chapter three, Lorentz's theory will be empirically equivalent to special relativity if and only if the generalized contraction hypothesis either is included among the basic assumptions of Lorentz's theory, or can be derived without any restrictions to particular experiments from other assumptions in the theory. After all, from a modern point of view, the generalized contraction hypothesis, which says that corresponding states physically transform into one another, is nothing but the assumption that the laws governing non-electromagnetic phenomena are Lorentz invariant, just as Maxwell's equations.

In sections 3.3.4 and 3.5.1, we saw that before 1905, Lorentz was basically satisfied with a derivation of the generalized contraction hypothesis in the context of (the vast majority of) optical experiments. In modern terms, he succeeded in deriving the generalized contraction hypothesis in this context by assuming the relativistic transformation behavior of forces and masses (see section 3.5.1). In Grünbaum's "doubly amended ether theory," which can be seen as a model for Lorentz's theory in the context of optics, the same goal is achieved by assuming, in modern terms, length contraction and time dilation (see section 3.5.2).

The Trouton-Noble experiment already illustrates that the doubly amended ether theory is not empirically equivalent to special relativity. To account for the negative result of this experiment, we need to assume that the non-electromagnetic forces that ensure the stability of the condenser transform the same way Coulomb forces do. With the assumptions Lorentz actually made to derive the generalized contraction hypothesis in the context of optics, the hypothesis holds in the case of the Trouton-Noble experiment as well. In other words, Lorentz's assumptions about the effect of ether drift on masses and forces ensure that, when an uncontracted condenser at rest in the ether producing a certain electromagnetic field configuration is set in motion, it turns into a contracted condenser producing the corresponding state of that field configuration in the co-moving frame. After the discussion in chapter three, we are in a much better position to understand why Lorentz phrased his explanation of the Trouton-Noble experiment the way he did:

> As to the experiments of Trouton and Noble, their negative result becomes at once clear, if we admit the hypotheses of § 8. It may be inferred from these and from our last assumption (§ 10) that the only effect of the translation must have been a contraction of the whole system of electrons and other particles constituting the charged condenser and the beam and thread of the torsion balance. Such a contraction does not give rise to a sensible change of direction. (Lorentz 1904b, pp. 189–190)

The crucial assumption to explain the negative result of the Trouton-Noble experiment, as Laue emphasized (see section 1.4.1), is that molecular forces transform the way Coulomb forces transform. Lorentz does not make that point. Understandably, especially given the criticism of Poincaré that he is just piling up hypotheses, Lorentz wants to show that his account of the Trouton-Noble experiment has the exact same structure as his account of optical experiments. The essential point is that corresponding states physically transform into one another, the field configuration by virtue of the Lorentz invariance of Maxwell's equations (which Lorentz had established for optics *and electrostatics* by 1904), the material components by virtue of the hypotheses going into the derivation of the generalized contraction hypothesis.

So, the actual 1904 version of Lorentz's theory, unlike Grünbaum's simplified model of the theory, can account for the Trouton-Noble experiment. This does not mean, of course, that the theory is empirically equivalent to special relativity. In the course of our discussion in chapters one through three, we have come across two important extra assumptions that are necessary to achieve this goal, and it is by no means clear that they will also be sufficient.

The first assumption is that we have to assume that the clocks of a moving observer register the 'local time' and not the real Newtonian time as Lorentz tacitly assumed before 1905 (see section 3.5.4). The assumptions introduced so far ensure that the rate of a clock is the rate of the local time, but they do not say anything about their synchronization. As long as observers use Einstein's light signaling method or any other purely electromagnetic process to synchronize their clocks, no new assumptions need to be added, but nothing prevents us from using a synchronization procedure involving non-electromagnetic and therefore potentially non-Lorentz invariant mechanisms.

My favorite example of such a mechanism is due to Jon Dorling. A good name for it would be the "Quentin Tarantino synchronization procedure."[1] It involves three people. Two of them—say, a clown and a joker—are given a watch and a gun. After sufficient target practice they are to position themselves at some distance from each other. The third person—let us call him Marvin—does not need any equipment at all. He is simply to stand in the middle. Unbeknownst to Marvin, who is told that the clown and the joker are settling some dispute in a western-style duel, the clown and the joker are actually about to check the synchronization of their watches in the following manner. At the moment their watches read 12 am, they shoot a bullet aimed straight at the spot where Marvin's head would be if he is still standing in the middle like he was told to. Afterwards, they check whether Marvin, now lying dead on the ground, has one or two bullets in his head. If they find two bullets, the clown and the joker conclude that their watches were properly synchronized, at least to a good enough

[1] I used to call it "cannonical synchronization." I am grateful to Sean Selby for introducing me to Tarantino's *Reservoir dogs*.

approximation. It will be clear that if we improve the accuracy of this procedure, it will only give the same result as the standard light signaling method if we assume Lorentz invariance for the laws governing the guns and the bullets.

The second assumption that needs to be added is the inertia of energy. Without this assumption, Lorentz's theory predicts that a sufficiently accurate repetition of the experiment Trouton originally performed at the suggestion of FitzGerald (see sections 1.4.1 and 2.5.2) would give a positive result. I will show in a moment how Lorentz's strategy of accounting for negative results of ether drift experiments with the help of the theorem of corresponding states and the generalized contraction hypothesis quite naturally leads to the introduction of $E = mc^2$ when applied to the Trouton experiment.

In *The theory of electrons*, one looks in vain for a statement that $E = mc^2$ needs to be incorporated in the ether theory if that theory is to be empirically fully equivalent to special relativity, as Lorentz claimed it was. This can mean two things. Either Lorentz mistakenly thought that he did not need $E = mc^2$ to make his theory empirically equivalent to special relativity, or he realized that he did but did not bother to say so explicitly. If one thinks about Lorentz and Einstein as candidates in a Senate race, as was customary in the seventies (see the introduction to part two), one would have to choose the former alternative. Otherwise, one has to attribute some highly uncharacteristic intellectual dishonesty[2] to Lorentz for not conceding that he was forced to take over an important proposal from his opponent's agenda. However, Lorentz's own understanding of his relation to Einstein was nothing of the sort. He simply preferred a different interpretation of an important feature of a formalism both he and Einstein accepted. It is thus perfectly respectable to believe that Lorentz accepted $E = mc^2$ although he does not explicitly say so in *The theory of electrons*.

There is, in fact, no shortage of documentary evidence to back up that belief. It is instructive, for instance, to compare the 1906 New York lectures of *The theory of electrons* to two other lecture series in which Lorentz discussed special relativity. I already cited these lecture series in chapters two and three. The first is a series of lectures held in Leiden in 1910–1912 devoted exclusively to special relativity (Lorentz 1922); the second is a series of lectures held at Caltech in 1922, published under the title *Problems of modern physics* (Lorentz 1927). Chapter five of Lorentz's Leiden lectures, entitled "The inertia of energy" (Lorentz 1922, pp. 238–254), contains a detailed and very lucid discussion of $E = mc^2$ (cf. section 2.5.2). It is clear from Lorentz's discussion that he fully accepts, not just $E = mc^2$, but all of relativistic mechanics, such as, for instance, the notion that every energy current corresponds to momentum (ibid., pp. 250–251). This is even clearer in the 1922 lectures at Caltech. Starting in section 36, entitled

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[2] See, for instance, Lorentz's rather naive confession to Einstein in 1915 that he came up with the contraction hypothesis in a completely *ad hoc* fashion (see section 3.2.6).

"Modification of the laws of dynamics," Lorentz covers relativistic mechanics including a detailed discussion of stress-energy-momentum (Lorentz 1927, pp. 107–125). Lorentz is clearly in full agreement with the results he presents. A quick scan of the table of contents of his *Collected Papers* (Lorentz 1934–39) shows that he even published on these subjects. I have not examined the relevant papers in any detail, but at first glance they only corroborate the impression one gets from Lorentz's lectures in Leiden and in California.

To return to the topic of this subsection, the need to incorporate $E = mc^2$ and relativistic mechanics in general clearly shows that it takes a lot more than the two assumptions of Grünbaum's doubly amended ether theory to make Lorentz's theory empirically fully equivalent to special relativity. And this underscores that Lorentz's theory is less attractive than Einstein's. The length contraction and time dilation effects of the doubly amended theory show that rods and clocks will never measure the true distances and the absolute time intervals in the Newtonian space-time posited by the theory. The hypotheses about force, mass, and energy clearly illustrate that all physical phenomena satisfy the rules of relativistic mechanics, and not the rules of Newtonian mechanics as one would expect in a Newtonian space-time. In the next section, I will indicate how these still somewhat vague misgivings about Lorentz's theory can be turned into a damning objection.

Before I do so, I want to show how one would naturally come to introduce $E = mc^2$ in Lorentz's theory in the context of the Trouton experiment (cf. section 2.5.2).

**4.1.2 Example 1: the Trouton experiment and the inertia of energy.** Suppose we try to account for the Trouton experiment in the same way that Lorentz accounted for the Trouton-Noble experiment on the basis of his 1904 theory. We start from a system which consists of a condenser that is being charged by some battery and which is at rest in the ether. We now consider which physical assumptions are needed to make sure that this system, when set in motion, turns into its corresponding state in the co-moving frame. Since the system at rest in the ether will not recoil when the condenser is charged or discharged, the system can not recoil in its corresponding state in the frame in motion through the ether either.

The theorem of corresponding states tells us that the field configuration in the moving condenser differs from the field configuration in the condenser at rest in two ways. First, it is contracted in the direction of motion by the familiar factor $\gamma$. Second, the field of the moving condenser carries electromagnetic momentum, while the field of the condenser at rest does not, because there is only an electric and no magnetic field. From Lorentz's hypothesis about the transformation of mass and force, it follows that the material part of the condenser will experience the exact same contraction as the field configuration. So far, the situation is fully analogous to the situation in the Trouton-Noble experiment.

What about the electromagnetic momentum? If we want to have momentum conservation in Lorentz's theory, and Lorentz does, we need another assumption to ensure that the system under consideration, when set in motion, will simply transform into its corresponding state in the co-moving frame. In modern terms: we need to add another assumption to ensure that the Lorentz boosted version of the original system will actually correspond to the system in motion. Without that extra assumption, the conservation of momentum would require the moving system to recoil, whereas with the condenser and the battery at rest we have no such effect.

From the discussion in section 2.5.2, it is clear that the assumption that needs to be added is the assumption of the inertia of energy. The recoil effect is an example of a violation of the center of mass theorem. Einstein showed in 1906 that $E = mc^2$ is a necessary and sufficient condition for avoiding such violations.

The upshot, then, is that the Trouton experiment provides a concrete example of how one goes about adding assumptions to Lorentz's theory if one wants to derive the generalized contraction hypothesis in a broader context than that of optical experiments that eventually boil down to the observation of a pattern of light and darkness. I want to emphasize that the addition of such assumptions will not make the theory *ad hoc* in the sense of compromising its testability. Since, in modern terms, the rationale for adding these hypotheses is simply to obtain a Lorentz invariant theory of ever widening scope, the hypotheses will come with all the excess empirical content they have in special relativity. The assumption that $E = mc^2$, introduced here to predict a strict null result for the Trouton experiment, forcefully illustrates this point.

Instead of adding hypotheses in a piecemeal fashion, one can take care of the anticipated null results of all conceivable ether drift experiments in one fell swoop by assuming that all physical laws are Lorentz invariant. For the purpose of the discussion in the next section, I will use this as a simplified model of the ether theory Lorentz claimed to be empirically equivalent to special relativity. I think this is a perfectly accurate model for the theory Lorentz actually held in the 1910s and 1920s, but to establish that claim would require a careful examination of all extant discussions of the post-1905 version of his theory, not just the discussions I have looked at in Lorentz's lectures of 1906, 1910–1912, and 1922 (Lorentz 1916, 1922, 1927). This is a project beyond the scope of this dissertation.

## 4.2 Why Einstein's interpretation of Lorentz invariance is preferable to Lorentz's

**4.2.1 How kinematical effects in special relativity come out as dynamical effects in Lorentz's theory: a 'common cause'-type argument for Minkowski space-time.** Once again, consider Grünbaum's doubly amended ether theory and compare it to special relativity in the context in which these two theories are empirically equivalent, i.e, in the context of optical experiments that eventually boil down to the observation of patterns of light and darkness. In particular, consider the hypotheses of length contraction and time dilation, the two amendments to the ether theory. According to the ether theory, the effects of length contraction and time dilation are due to peculiarities of all laws governing physical systems, causing them to deviate from the normal spatio-temporal behavior in the Newtonian space-time posited by the theory. In special relativity, these phenomena are simply part of the normal spatio-temporal behavior of systems in Minkowski space-time (cf. the discussion in section 2.3.5).

As long as it is a live option that all of physics will ultimately be reduced to electrodynamics, the ether theorist has good reason to the insinuating phrase "peculiarities of all physical laws" with which I discredited his position in the preceding paragraph. He would point out that, in due course, all these peculiarities will be reduced to some basic properties of the very small set of equations (i.e., Maxwell's equation and the equation for the Lorentz force) that form the basis of the electromagnetic world picture.

However, as I have mentioned repeatedly now, a purely electromagnetic ether theory, set in a Newtonian space-time, which, at the same time, predicts null results for all optical ether drift experiments, so as to be empirically equivalent to special relativity, at least in this context, had ceased to be an option by 1906. The ether theorist now has to accept that the laws of electrodynamics do not exhaust the list of physical laws, and to keep his theory viable empirically, he has to assume that the additional laws, no matter how different they are from Maxwell's equations, must at least be such that all non-electromagnetic systems experience the same contraction and dilation effects as the electromagnetic ones.

Let me make the same point in a slightly different way. Barring the discovery of a new unifying scheme to replace the now bankrupt electromagnetic view of nature, the ether theorist has to accept some unexplained coincidences in the physical world, whereas the relativist can account for these coincidences simply by pointing to the space-time structure posited by her theory. Put this way, the observation suggests that we can mount a 'common cause'-type argument to justify one's preference for special relativity over the doubly amended ether theory, even in the limited context of optics we are considering in which the two theories are empirically equivalent.[3] The contraction of physical systems and the retardation of processes in such systems when the system is set in motion, no matter whether the system is of an electromagnetic or of a non-electromagnetic nature, are effects that seem to have a common cause in special relativity, but that are due to unexplained coincidences in the ether theory.

The reason for calling this a 'common cause'-type argument rather than a common cause argument, is that Minkowski space-time does not seem to be a common cause in quite the same sense that a shrimp cocktail contaminated with the salmonella bacteria is the common cause of the sudden death of half the population of a cheap Dutch old folks home.[4] It would be very interesting to examine the relation between my 'common cause'-type argument and the common cause argument Wesley Salmon has (more cavalierly) put forward for molecular reality (Salmon 1984, pp. 213–227; 1989, pp. 124–126), especially since it is widely accepted that Salmon's beautifully simple argument does actually capture the rationality of believing in the existence of atoms. Unfortunately, this is yet another project beyond the scope of this dissertation.

What I want to do instead is to develop this 'common cause'-type argument in a historically more realistic setting. I want to remove the restriction to optics and I want to replace the doubly amended ether theory by the final version of Lorentz's ether theory, or rather by a conveniently simplified model of that theory in which we assume universal Lorentz invariance to ensure that the generalized contraction hypothesis holds no matter which ether drift experiment we are considering (cf. the discussion in section 4.1). We can run the exact same 'common cause'-type argument that we used before that justify our preference for special relativity over this empirically equivalent ether theory.

However, we can now substantially strengthen this argument. So far, we only looked at length contraction and time dilation. In other words, we only used the Lorentz transformation equations for the space-time coordinates. These are basically the only Lorentz transformation equations we need to deal with the type of optical experiment we considered in the case of the doubly amended theory. Nothing stops us from considering experiments in which other Lorentz transformation equations play a role. The non-optical experiments that I have been looking at in chapters one through three, the condenser experiments of Trouton and Noble and the electron experiments of Kaufmann and others, involve the Lorentz transformation equations for the energy-momentum tensor. Both the velocity dependence of the mass of the electron measured in Kaufmann's experiments and the delicate balanced turning couples measured in the Trouton-Noble experiment follow directly from the transformation properties of the energy-

[3] I found and developed the idea of a 'common cause'-type argument for Minkowski space-time in discussions with John Norton. Unfortunately, I have not yet had a chance to discuss this idea with Wesley Salmon.

[4] This example is based on a true story.

momentum tensor for these systems. So, for the relativist, these effects simply reflect the structure of the Minkowski space-time posited by her theory. For the ether theorist, on the other hand, it is an unexplained coincidence that the stress-energy-momentum of both the electromagnetic and the non-electromagnetic parts of the Lorentz-Poincaré electron and the Trouton-Noble condenser can be described by a quantity that transforms as a second rank tensor under Lorentz transformation, which, in fact, is just the property of these systems that accounts for the results of Kaufmann and Trouton and Noble. For the ether theorist, the Lorentz transformation has nothing to do with the structure of the Newtonian space-time posited by his theory.

In this way, we find more effects—and, even more important, a wider variety of effects—that have Minkowski space-time as their 'common cause' in special relativity, but are no more than curious coincidences in an empirically equivalent ether theory. Although the status of the 'common cause' obviously needs further philosophical clarification, it is safe to say, I think, that this is a very strong argument for preferring special relativity over an empirically equivalent classical ether theory. To be more precise, it is a very strong argument to prefer Einstein's interpretation of Lorentz invariance as a symmetry of Minkowski space-time over Lorentz's interpretation of Lorentz invariance as a property accidentally shared by all physical laws governing physical systems in a Newtonian space-time.

Another way to argue for the superiority of Einstein's interpretation of Lorentz invariance over Lorentz's would be to show that the ether theory in the form in which it is empirically equivalent to special relativity violates the symmetry principles that John Earman has formulated to judge whether the symmetries of the space-time structure of a theory are commensurate with the relevant symmetries of the dynamical laws (Earman 1989, p. 46). The relevant symmetry transformations in Lorentz's ether theory are the Galilean transformation and the Lorentz transformation. The former expresses a symmetry of the space-time of the theory and *corresponds* to what Earman calls a 'space-time symmetry.' The latter expresses a symmetry of the dynamical laws governing the systems in the space-time and *corresponds* to what Earman would call a 'dynamical symmetry.' Earman's symmetry principles say that every space-time symmetry should be a dynamical symmetry and vice versa. In Lorentz's ether theory, these principles *would seem to be* violated.

The reason I did not pursue this approach here is twofold. The first reason is a technical one and accounts for the italicized words of caution in the preceding paragraph. The clean way to state Earman's symmetry principles is in terms of certain diffeomorphism that map the space-time manifold back onto itself dragging along various geometric object fields defined on the manifold. For a rigorous statement of the violation of these principles by Lorentz's ether theory, one would therefore first have to formulate that theory in these terms. Robert Rynasiewicz told me he is currently working on such a geometric formulation of Lorentz's theory. The analysis I suggested above is best postponed, I think, till the result of his efforts has become available.

The following problem will illustrate why I think such a reformulation of Lorentz's theory is really called for in this case and is not just another pointless project in the booming industry of rewriting space-time theories from Aristotle to Einstein in the language of modern differential geometry, an academic fad that may prove as harmful to the rational reconstruction of the history of science as the seventies fad to force historical episodes into the straightjacket of one's favorite model for theory change has been; and maybe even more so given the rising tide of anti-rationalism in the history of science.

Intuitively, the Lorentz transformation is a dynamical symmetry, but not a space-time symmetry in Lorentz's ether theory. But we can easily define a transformation that would make it look as if it is both. In fact, the way Lorentz used the Lorentz transformation in combination with the Galilean transformation before 1905 makes it look this way. Lorentz's theorem of corresponding states shows how starting from a field configuration where the fields are given as functions of the space-time coordinates of a Galilean frame at rest in the ether, we can construct a new field configuration where the fields are given as functions of the space-time coordinates of a Galilean frame moving through the ether. One would expect that in a coordinate free reformulation of the theory, this transformation from one model of the theory to another would not come out as a diffeomorphism affecting only the geometric object fields describing the contents of Lorentz's Newtonian space-time and not the geometric object fields encoding the space-time structure.

My second reason for not pursuing this approach has to do with another task I identified for historians of special relativity, viz. to articulate exactly what Lorentz's contemporaries meant when they denounced his theory as *ad hoc*. My hunch is that my 'common cause'-approach to the question of what makes Einstein's interpretation of Lorentz invariance preferable to Lorentz's will be more fruitful in that context than the more rigorous but also more abstract approach suggested by Earman's work. In particular, the 'common cause'-approach looks more promising for working out the (dangerously) obvious historical parallel between recognozing that Minkowski space-time is the 'common cause' of Lorentz invariance and recognizing that the fact that planets orbit around the sun is the 'common cause' for some unexplained correlations in Ptolemaic planetary astronomy involving the radii of the epicycles of outer planets and the deferents of inner planets.[5] One has to be very careful exploiting such historical parallels and I will therefore not pursue this line of thought here.[6]

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[5] Poincaré exploited this same analogy for somewhat different purposes in his well-known paper "On the dynamics of the electron" (I am grateful to John Norton for reminding me of this):

**4.2.2 Example 2: the Trouton-Noble experiment and the Laue effect.** The Laue effect, manifesting itself in the delicately balanced turning couples on the moving condenser of the Trouton-Noble experiment, is an example of an effect which in special relativity is "caused" by Minkowski space-time, whereas in Lorentz's theory, it is nothing but a curious contingent fact. Laue's definition of the effect that I named after him was that a stressed body in static equilibrium and in uniform motion needs a turning couple to sustain that motion (see, e.g., Laue 1911a, p. 149). It is a direct consequence of the fact that under the standard definition of the four-momentum of spatially extended systems, stresses in one frame can give rise to energy and momentum in others.

In chapter two, I argued that the Laue effect is purely kinematical in special relativity (see especially section 2.3.5). This argument turned on the observation that the effect can be defined away by changing our convention about picking space-like hyperplanes in the definition of the four-momentum of spatially extended systems (see section 2.2.3). I showed that the Laue effect is an artifact of the standard, what I called, 'Laue definition' of this quantity. Under the alternative 'Rohrlich definition' we do not find the effect. Under the Rohrlich definition, stresses in one frame do not contribute to the momentum in others.[7] As a consequence, there

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> Let us imagine some astronomer before Copernicus, pondering upon the Ptolemaic system. He would notice that, for every planet, either the epicycle or the deferent is traversed in the same time. This cannot be due to chance, and there must be some mysterious bond between all the planets of the system.
>
> Then Copernicus, by a simple change of co-ordinate axes which were supposed fixed, did away with this seeming relationship: every planet described one circular orbit only, and the periods of revolution became independent of one another—until Kepler once more established the relationship that had apparently been destroyed.
>
> Now, there may be an analogy with our problem. If we assume the relativity postulate, we find a quantity common to the law of gravitation and the laws of electromagnetism, and this quantity is the velocity of light; and this same quantity appears in every other force, of whatever origin. There can only be two explanations.
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> Either everything in the universe is of electromagnetic origin; or, this constituent which appears common to all the phenomena of physics has no real existence, but arises from our method of measurement. What are these methods? One might first reply, the bringing into juxtaposition of objects regarded as invariable solid things; but this is no longer so in our present theory, if the Lorentz contraction is assumed. In this theory, two lengths are by definition equal if they are traversed by light in the same time.
>
> Perhaps the abandonment of this definition would suffice to overthrow Lorentz's theory as decisively as the system of Ptolemy was by the work of Copernicus. (Poincaré 1906, pp. 148–149).

[6] I am grateful to Ofer Gal for sharing his expertise in 17th century science with me in informal discussions of this issue.

[7] Let me remind the reader of the quick way to see this. Rohrlich defines the four-momentum as the integral of the energy density and momentum density components of the energy-momentum tensor over a hyperplane of simultaneity in (the most plausible candidate for) the system's (instantaneous) rest frame. This quantity transforms as a four-vector under Lorentz transformation. So, the four-momentum in a new frame cannot pick up contributions from the stress components of the energy-momentum tensor in the (pseudo) rest frame.

will be no turning couples on stressed bodies in uniform motion. Since the only difference between the Laue definition and the Rohrlich definition lies in the convention about picking space-like hyperplanes, and since the Laue effect is present under the former definition but not under the latter, it follows that it is a purely kinematical effect.

In arguing for the kinematical nature of the Laue effect, I pointed out that the kinematical nature of length contraction can be understood along similar lines (see section 2.3.5). length contraction is an artifact of which space-like slice of an object's bundle of worldlines we pick in defining its length.

This analysis clearly brings out why the length contraction effect and the Laue effect cannot be kinematical effects in a theory positing a Newtonian space-time. One of the most important features of Newtonian space-time, and certainly one of the features dearest to Lorentz's heart (see section 3.5.7), is absolute simultaneity. From a relativistic point of view, this means that there is a preferred way of taking time slices. An ether theorist such as Lorentz subscribing to a theory empirically equivalent to special relativity but positing a Newtonian space-time, will attach special importance to hyperplanes of simultaneity in a frame at rest in ether.

This is what is responsible for the fact that, in Lorentz's theory, the contraction of a rod with respect to the ether has a very different status than the contraction of a rod with respect to a frame of reference which is itself moving with respect to the ether (see section 3.5.5). A similar observation applies to the Laue effect. Instead of being a kinematical effect, as in special relativity, the Laue effect will be a combination of dynamical effects and artifacts of measurement in Lorentz's theory. The energy, momentum, angular momentum, and turning couples on a moving charged condenser coming from the stresses in the condenser's rest frame will be purely dynamical effects if the condenser is in motion and the observer is at rest with respect to the ether, they will be nothing but artifacts of measurement if the observer is in motion and the condenser is at rest with respect to the ether, and they will be a combination of the two if condenser and observer have different velocities with respect to the ether.

For the sake of convenience, I consider the case where the observer is at rest and the condenser is in (uniform) motion with respect to the ether. And to bring out as forcefully as I can how unsatisfactory the interpretation of the Laue effect is in an ether theory that retains absolute simultaneity, I will not look at the Trouton-Noble experiment itself, but at the slight variation of the experiment that I discussed in section 2.3.5. In other words, I will directly consider the electromagnetic and non-electromagnetic momentum coming from the stresses in the condenser's rest frame, rather than the turning couples to which these momenta give rise.

Because of the preferred status of frames at rest in ether, our ether theorist will define the real energy and the real momentum of a spatially extended system as integrals of the energy density and momentum density components of the system's energy-momentum tensor over a hyperplane of simultaneity in a frame at rest in the ether (and *not*, for instance, over a hyperplane of simultaneity in the system's rest frame). For the experiment I am considering of an observer at rest and a condenser in motion with respect to the ether, the ether theorist's definition of the real energy and real momentum of the system is therefore equivalent to the Laue definition of the four-momentum of the system in the observer's rest frame. So, the real electromagnetic and non-electromagnetic momentum in the condenser in this case are given by the relativistic equations for $\mathbf{P}^{L}_{EM}$ and $\mathbf{P}^{L}_{non\text{-}EM}$ ('L' for Laue) I derived in section 2.3 (see Eqs. 2.107–2.108).

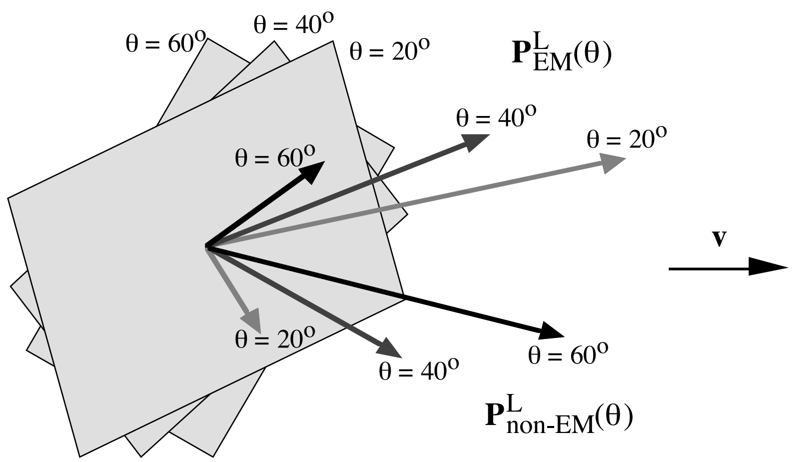


Figure 4.1 The Laue effect in a variant on the Trouton-Noble experiment.

Figs. 4.1–4.2 (cf. Fig. 2.7 in section 2.3.4)[8] are meant to remind the reader of the counter-intuitive effects encoded in these definitions, effects that for the ether theorist are due to peculiarities of the dynamical laws governing systems in a Newtonian space-time, whereas—let me emphasize this again—for a relativist they simply reflect the structure of Minkowski space-time.

A charged condenser moving through the ether at 75% the speed of light, a system in static equilibrium, is slowly and adiabatically being rotated around an axis perpendicular to its velocity. What happens, as one can see in Fig. 4.1, is that the vectors representing the electromagnetic momentum ($\mathbf{P}^{L}_{EM}$) and the non-electromagnetic momentum ($\mathbf{P}^{L}_{non\text{-}EM}$) also rotate as the condenser rotates, the electromagnetic momentum getting smaller as the angle θ between the plates of the condenser and its velocity **v** goes from 20 to 40 to 60 degrees, the non-electromagnetic momentum getting bigger. The total momentum remains fixed and in the

[8] I am grateful to David Sandborg for writing a computer program producing the basic diagram on the basis of Eqs. 2.107–2.108 and the geometry of the contracted condenser, and to Suzanne Durkacs for importing the results into the software I used and for suggesting to put a few of these diagrams on top of one another to illustrate the effect. The diagrams of Sandborg that I used for Figs. 4.1–4.2 are for a velocity 75% the speed of light.

direction of motion (see Fig. 4.2), but there is a flow of momentum from the electromagnetic to the non-electromagnetic part of the system as θ goes from 0 to π/2. As θ goes from π/2 to π, the momentum flows back from the non-electromagnetic to the electromagnetic part. This process is repeated as θ goes from π to 2π. Given that the system is in static equilibrium, this is a rather odd effect.

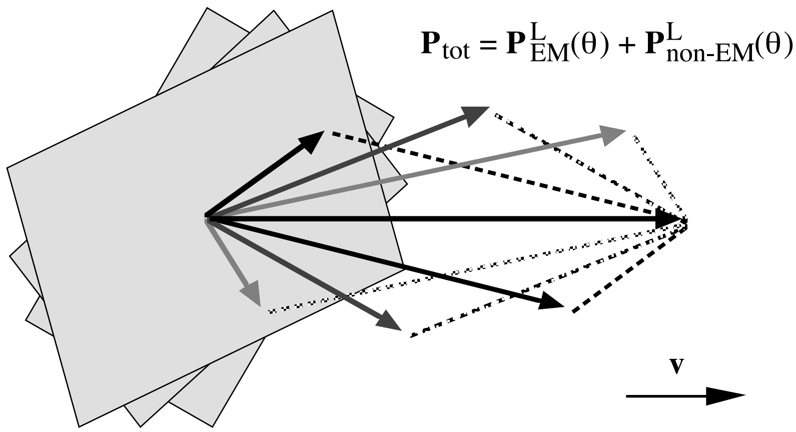


Figure 4.2 The conservation of total momentum in a rotating moving condenser.

I would like to think that if Einstein had shown these figures to Lorentz and had told him that, in special relativity, this curious exchange of momentum between different parts of this system can simply be understood as an artifact of arbitrarily carving up space-time one way rather than another, Lorentz would have given up the comfort of holding on to the familiar Newtonian notion of absolute simultaneity.[9] Unfortunately, Einstein did not do a very good job at all convincing Lorentz of the virtues of his theory, and of the importance of the crucial insight that lies at the heart of it, the relativity of simultaneity.

[9] If we are going to engage in some 'what if'-history, we can also ask the question how J. S. Bell would have reacted to the effect illustrated in Figs. 4.1–4.2, and to my 'common cause'-type argument for Minkowski space-time in general. Recall that Bell seriously suggested a return to pre-relativistic ether theory. In the interview from which I quoted in section 2.3.5, he called such a move "the cheapest solution" to the problems raised by the Einstein-Podolsky-Rosen paper, the Bell inequalities, and the Aspect experiments. He elaborated: "Behind the apparent Lorentz invariance of the phenomena, there is a deeper level which is not Lorentz invariant" (Davies and Brown 1986, p. 49). To which we may add (as has been urged by Keith Parsons) that it is certainly possible that the fossil record was planted by the Devil to lead Creationists into temptation.

## 4.3 Why Lorentz failed to appreciate Einstein's new kinematics

**4.3.1 Theories of principle versus constructive theories.** One way of stating the upshot of Einstein's 1905 paper is to say that, whatever the world is like, it has to be such that it satisfies the two basic postulates of the theory, the relativity principle and the light postulate. This reading would fit with Einstein's later assessment (Einstein 1919, p. 228) of the special theory of relativity as a theory of principle (in which phenomena are explained by showing that they are necessary consequences of the basic postulates of the theory) rather than a constructive theory (in which phenomena are explained by showing that they are adequately described by the models of the theory).[10] When we read Einstein's 1905 paper in this way, there seems to be no reason to prefer one concrete model of a world satisfying the two postulates over another. From this point of view then, there is no reason to prefer the model universally accepted today, based on a Minkowski space-time,[11] over a Lorentzian model, based on a Newtonian space-time.

The interpretation of Einstein's 1905 paper as putting forward a theory of principle in the strict sense explicated above is clearly too narrow. The way in which the paper is divided into a kinematical and an electrodynamical part already makes it clear that Einstein favors a model of a world satisfying his postulates based on a Minkowski space-time. This is notwithstanding such historical complications as Einstein's initial lack of appreciation for Minkowski's work and Minkowski's understanding of his own work in terms of the electromagnetic view of nature (see section 3.5). Einstein intended his theory to provide a new kinematics, not a convenient axiomatization of a Lorentzian dynamical theory. However, Lorentz, I think, did see the difference between special relativity and his own theory as the difference between a theory of principle and a constructive theory in the strict sense in which I distinguished these two types of theories above. This, I take it, is the point of the often quoted passage from the final section of *The theory of electrons*,[12] where Lorentz writes: "Einstein simply postulates what we have deduced [...] from the fundamental equations of the electromagnetic field" (Lorentz 1916, p.230[13]). In the early years of special relativity, it was much harder to see than with 90 years of

[10] As Einstein wrote in 1946 in his autobiographical notes, in a passage that has often been quoted (see, e.g., Holton 1988, pp. 309–310; Schaffner 1974, p. 62): "By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results. The example I saw before me was thermodynamics" (Einstein 1949, p.53). On the role of thermodynamics in Einstein's thought, see Klein 1967.

[11] This, of course, shows that the prospects for a constructive theory were not as bleak as Einstein thought when he developed special relativity (see the preceding footnote).

[12] See, for instance, Holton 1969, p. 322; Schaffner 1969, pp. 509–510; 1974, p. 48; 1976, p. 465; Nersessian 1984, p. 114; 1986, p. 206.

[13] See section 3.5, where I quoted this section in its entirety, for the context of Lorentz's remark. Notice that Lorentz, in his characteristically generous way, concedes in this same passage that Einstein's theory, understood as a theory of principle, has certain advantages over his own.

hindsight that Einstein's theory not only has a logical structure that is very different from Lorentz's, but also a very different space-time ontology. As we saw in section 3.5, Lorentz was not the only one having trouble to see this clearly. Let me repeat the passage I quoted from Klein's discussion of Ehrenfest's inaugural lecture "On the crisis of the light ether hypothesis" in Leiden in late 1912: "Ehrenfest did not discuss the basic revision of the concepts of space and time that lay at the heart of Einstein's theory; he limited himself to pointing out that the results of the relativity theory were indistinguishable from those obtained by Lorentz, despite the fundamentally different logical structures of the two theories" (Klein 1970, p. 5).

To further dispel the worry that my interpretation of Lorentz's understanding of special relativity is too uncharitable, I want to examine two concrete factors that, I suspect, either were partly responsibly for Lorentz's reading of Einstein's work as proposing a theory of principle in an overly narrow sense, or, at least, strongly reinforced that reading.[14] What I have in mind are Einstein's derivations in his 1905 paper of the transformation equations for charge density and for mass. Einstein derived both these equations directly from his postulates. For Lorentz, this obscured the fact that they express kinematical relations rather than dynamical ones. It is noteworthy that both these transformation equations play an important role in the same passage in which Lorentz made his remark that Einstein simply postulates what he had derived from Maxwell's equations.

**4.3.2 Example 3: the transformation of charge density.** In his 1905 paper, the transformation of charge density is the last element Einstein examines in his proof that Maxwell's equations including the source terms are invariant under Lorentz transformation. The transformation behavior of the space and time coordinates has already been settled at that point, as has the transformation behavior of the electric and magnetic fields. Moreover, the addition theorem for velocities has fixed the transformation behavior of the velocity field multiplying the charge density to give the current density. The transformation formula for charge density is thus the only piece left at this point and can therefore be found directly from the requirement that Maxwell's equations satisfy the relativity principle. As I argued in section

[14] I am not the first to claim that Lorentz missed the crucial point that Einstein had introduced a new kinematics. Jon Dorling has written "that it is a psychological fact about Lorentzians that they have not been able to understand how the Einstein-Minkowski alternative purports to explain the facts in question [i.e., relativity of simultaneity, length contraction, time dilation]" (Dorling 1968, p. 68). When I asked him years ago, Dorling hesitated to include Lorentz himself among the "Lorentzians." He told me his comment was directed to latter day Lorentzians such as Prokhovnik. Unlike Dorling, I do not think it overly uncharitable to include Lorentz himself. What makes this acceptable, I think, is the historical fact that neither Einstein nor Minkowski made it very clear what Dorling's "Einstein-Minkowski alternative" is supposed to be. In Einstein's case, matters were obscured by his presentation of special relativity as a theory of principle, whereas Minkowski, as I mentioned before, saw his own work as a contribution to the electromagnetic view of nature.

3.5, this is exactly what Einstein does, rendering his proof of the Lorentz invariance of Maxwell's equations circular. It was precisely this circularity, I suggested, that Lorentz was referring to when he wrote in the final section of *The theory of electrons*: "I have not availed myself [of Einstein's transformation law for charge and current density, because they] are rather complicated and look somewhat artificial, *unless one deduces them from the principle of relativity itself*" (Lorentz 1916, p.230, my italics).

It was only after Lorentz had found a derivation of these transformation equations in terms of what the modern reader recognizes as the relativity of simultaneity, length contraction, and time dilation (see section 3.5.6), that he started using the relativistic transformation equations for charge and current density. From a modern point of view, both Lorentz's and Einstein's derivation of the transformation equation for charge density can be seen as a proof that charge density forms the time component of a four-vector in Minkowski space-time. There are two differences between these two proofs. First, Einstein, in using the Lorentz invariance of Maxwell's equations, used the principle of relativity itself, whereas Lorentz did not. Second, the relativistic interpretation of Lorentz's proof would be very different from Lorentz's own interpretation of his proof. For Lorentz, the various elements in his derivation (relativity of simultaneity, length contraction, time dilation) are combinations of dynamical effects and artifacts of measurement. In special relativity, these same elements are kinematical effects. I claim that Lorentz did not appreciate this second difference, coming from the 'kinematics/dynamics distinction,' since he was focused on the first, coming from the 'theory-of-principle/constructive-theory distinction.'

**4.3.3 Example 4: the transformation of mass.** In his 1905 paper, Einstein also derived the transformation equation for mass directly from the principle of relativity, this time in conjunction with the requirement that Newton's second law be valid in the limit of small velocities. If we replace the transformation law for forces that Einstein used in his 1905 paper by the transformation law that Planck used in 1906, Einstein's derivation becomes equivalent to a derivation already given by Lorentz in 1899, provided that we set some undetermined factor in Lorentz's derivation equal to unity, as Lorentz himself would do in 1904 (see sections 3.3. and 3.4)

The point of Lorentz's 1899 derivation was to find how mass should transform in a theory that would give the general prediction that we cannot detect ether drift through optical experiments that eventually boil down to the observation of a pattern of light and darkness. In modern terms, Lorentz's goal was to make sure that, at least in almost all of optics, a principle of relativity obtains in a world modeled by his theory. Lorentz did not leave it at that. In 1904, he constructed a model for the electron and showed that it had an electromagnetic mass transforming exactly as demanded by this limited principle of relativity if the undetermined factor in his 1899 derivation were set to unity (see section 3.4). This is a clear example of Lorentz deducing something from the fundamental equations of the electromagnetic field that Einstein simply postulated. As a matter of fact, the very sentence in which Lorentz complains that Einstein simply postulates what he can deduce (albeit it with some problems) contains a reference to Kaufmann's experiments in which the Lorentz-Einstein transformation equation for mass was subjected to an empirical test:

> [Einstein's] results concerning electromagnetic and optical phenomena (*leading to the same contradiction with Kaufmann's results that was pointed out in §179*) agree in the main with those which we have obtained in the preceding pages, *the chief difference being that Einstein simply postulates what we have deduced, with some difficulty and not altogether satisfactorily, from the fundamental equations of the electromagnetic field*." (Lorentz 1916, pp. 229–230; my emphasis).

Lorentz's "not altogether satisfactorily" probably refers to the fact that he had to add a non-electromagnetic piece to his electron model to take care of the inconsistency spotted by Abraham and Poincaré (see section 3.4).

The example of the transformation of mass is both historically more important and conceptually more complicated than the example of the transformation of charge density.

It is historically more important because the early reception of Einstein's theory took place in the context of experiments by Kaufmann and others to decide between the Einstein-Lorentz and the Abraham predictions for the velocity dependence of the transverse mass of the electron (see Miller 1981).

It is conceptually more complicated for several reasons. The first is directly related to the Kaufmann experiments. In the case of the transformation of charge density there are two distinctions to keep straight: the 'kinematics/dynamics distinction' and the 'theory-of-principle/constructive-theory distinction.' Here we have a third: the distinction between the 'Lorentz-Einstein relativity postulate' and the 'Abraham electrodynamic postulate' (see Planck 1906 and section 3.4). The fact that the theories of Lorentz and Einstein agree on the transformation equation for mass must have seemed far more important at the time than the fact that these equations are interpreted differently in the two theories.

What complicates matters even further is (a) that, in the case of mass, the 'kinematics/dynamics distinction' is much harder to appreciate than the 'theory-of-principle/constructive-theory distinction,' and (b) that the 'kinematics/dynamics distinction' in the case of mass is much harder to appreciate than the 'kinematics/dynamics distinction' in the case of charge density. In fact, the 'kinematics/dynamics distinction' in the case of mass can only be stated cleanly with the help of Laue's work of 1911. At that point, it became clear that the relativistic transformation equation for mass is a direct consequence of the fact that the four-momentum of any closed system[15] transforms as the four-momentum of the relativistic point particle Einstein had considered in 1905. As Pais put it in a passage I quoted at the end of section 3.4: "Special relativity killed the classical dream of using the energy-momentum-velocity relations of a particle as a means of probing the dynamical origins of its mass. The relations are purely kinematical" (Pais 1982, p. 159). As is illustrated by the following quotation from his 1922 lectures at Caltech, Lorentz would eventually come to realize that it is impossible to use the energy-momentum-velocity relations to probe the dynamical origins of the mass of electrons, but not that this is because these relations simply reflect the Minkowski space-time structure. Lorentz explained this impossibility in terms of the principle of relativity instead, which for him was perfectly compatible with a Newtonian space-time and absolute simultaneity (see Lorentz 1927, pp. 220–221):

> **42. Structure of the Electron.** The formula for momentum was found by a theory in which it was supposed that in the case of the electron the momentum is determined wholly by that of the electromagnetic field; namely,
>
> $$\frac{1}{c}[\mathbf{EH}] \text{ per unit volume.}^{[16]}$$
>
> This meant that the whole mass of an electron was supposed to be of electromagnetic nature. Then, when the formula for momentum was verified by experiment, it was thought at first that it was thereby proved that electrons have no "material mass." Now we can no longer say this. Indeed, *the formula for momentum is a general consequence of the principle of relativity*, and a verification of that formula is a verification of the principle and tells us nothing about the nature of mass or of the structure of the electron. Therefore physicists are absolutely free to form any hypotheses on the properties and size of electrons that may best suit them. [...]
>
> Of course I need hardly mention that, whatever theory we favor, we must suppose that a motion of translation will make the electron contract. Indeed, we want to apply the principle of relativity to the electron also; if then we know what is going on in the electron when it has no motion of translation, we can deduce from the principle in full detail the state that will exist when there is such a motion. (Lorentz 1927, pp. 125–126; my emphasis)

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[15] Strictly speaking, Laue only proved this for closed *static* systems (see section 2.1).

[16] In my notation and in SI units, this would be $\varepsilon_0 \, \mathbf{E} \times \mathbf{B}$ (cf. section 1.4.1, Eq. 1.35, and section 2.1.1, Eq. 2.4).