Does the Mere Notion of a Frozen Light Wave Discredit the Electromagnetic Ether?

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Abstract

This paper addresses a current debate in the philosophy of physics, concerning whether and in what sense Albert Einstein's *Chasing the Light* thought experiment was significant in his development of the theory of special relativity. While Einstein granted this thought experiment pride of place in his 1949 *Autobiographical Notes*, philosophers and physicists continue to debate what the thought experiment actually establishes. I claim that we ought to think of *Chasing the Light* as Einstein's first attempt at problematizing the idea of the electromagnetic ether, thereby contributing to his eventual adoption of the light postulate. This interpretation requires one to presuppose the principle of relativity when considering *Chasing the Light*, and my argument is unique insofar as it provides evidence for the conceptual and historical plausibility of this presumption. My argument directly challenges John D. Norton's compelling claim that *Chasing the Light* is best understood as a refutation of emission theories of light propagation. While both interpretations of the thought experiment are conceptually coherent, the interpretation found in this paper is more straightforwardly supported by historical evidence.

I. Introduction

In Albert Einstein's 1949 *Autobiographical Notes*, he describes a thought experiment that seems to have been an early idea from which he eventually developed special relativity. He claims, "at the age of sixteen", to have considered the problem now famously known as 'Chasing a Light Beam' or '*Chasing the Light*':

> "If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell's equations. From the very beginning it appeared to me in-

> tuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for an observer who, relative to the earth, was at rest. For how, otherwise, should the first observer know, i.e., be able to determine, that he is in a state of fast uniform motion?" (Einstein 1949 in Schilipp 1951, p. 53).

Peacock (2016, 5) notes that this thought experiment's importance is "open to question", as it is not clear how *Chasing the Light* proceeds toward any interesting component of special relativity. However, commentators seem to agree on at least one point: the central problem posed by *Chasing the Light* concerns what one would see "if one could catch up with a light ray", and therefore observe it as frozen (Peacock 2016, 6). The debate is then about how the strange hypothetical phenomenon of observing a motionless light wave could have meaningfully contributed to Einstein's development of special relativity.

This paper addresses the problem of whether and in what sense this thought experiment was significant in the development of special relativity, from both conceptual and historical perspectives. I begin by following John D. Norton's (2004) account of the issue that perplexes commentators: Einstein credits the thought experiment with a great deal of importance, while it remains unclear exactly what the experiment establishes. Norton proposes that we resolve this issue by conceiving of the experiment as an argument against emission theories of light, rather than ether theory. I argue instead that the thought experiment's importance is clearer if we (a) adopt the principle of relativity as one of its presumptions, and (b) shift the focus of the experiment from frozen light to any change in the speed of light as an observer moves through the ether. I conclude that this thought experiment is best understood as an argument against the notion of the 'electromagnetic ether', and as a potential contributor to the eventual adoption of the light postulate.

In Section II, I briefly summarize the theory of special relativity and its constitutive postulates. Section III contains a description of Norton's interpretation of *Chasing the Light*, and Section IV contains my alternative interpretation of the thought experiment. In Section V, I present some conceptual and historical considerations in order to argue that my interpretation is at least as interesting and plausible as Norton's account. Section VI provides a more detailed and formal elaboration of the geometric argument presented in Section V. Finally, in Section VII, I provide further historical evidence to suggest that my interpretation may be preferable to that of Norton, or that it is possible that the two interpretations are compatible.

II. A Brief Overview of Special Relativity

Let me begin by briefly summarizing the two theoretical assumptions upon which special relativity came to be derived: the principle of relativity and the light postulate. The principle of relativity holds that the laws of physics must be the same in all inertial reference frames. This principle entails that an observer cannot perform any experiment that reveals their *absolute motion* through space: for the possibility of discovering one's *absolute motion* would require the existence of a reference frame at absolute rest, thereby distinguishing this rest frame as having its own unique statements of the laws of physics. Therefore, according to the principle of relativity, an observer can only detect relative motion with respect to other bodies.

The light postulate holds that the speed of light must always be the same - roughly 300,000 kilometers per second or simply 'speed c' - regardless of the inertial frame in which it is observed. This postulate arose out of the predictive success of Maxwell's equations in electrodynamics, and the failure of any other theory to match this success. Using only these two theoretical assumptions, theoreticians can derive every unorthodox physical effect associated with special relativity, including time dilation, length contraction and the relativity of simultaneity.

III. Norton's Interpretation of '*Chasing the Light*'

Norton contends that, as an argument against ether theory, *Chasing the Light* is unconvincing. The ether theory holds that the speed at which light propagates in a vacuum is always c with respect to the electromagnetic or 'luminiferous' ether, which is itself in a state of absolute rest; the mechanics of this theory are specified by Maxwell's equations.[1] Einstein notes two concerns about the phenomenon of a standing light wave: (1) we have never observed standing light "on the basis of experience", and (2) standing light is not allowed "according to Maxwell's equations" (Einstein 1949, 53). Nevertheless, Norton points out that the ether theorist could easily address both of these concerns (Norton 2004, 75-76).

Concern (1) arises because we have never observed a standing beam of light. However, the thought experiment entails that witnessing standing light requires the observer to be travelling at speed c through the ether. The ether theorist's response is simple: we have never moved at speed c with respect to the ether, so concern (1) is unjustified.

Moreover, Norton shows that concern (2) is outright incorrect: using Maxwell's equations, one can transform the unprimed ether frame (t, r) to a primed frame (t', r') using t = t' and r = r' + vt', where the velocity of the frame v matches the velocity of the propagation of the light wave. The light wave in this new frame is 'frozen', although "spatially oscillating", as predicted in *Chasing the Light* (Norton 2004, 76). Thus, the ether theorist would have no trouble refuting concern (2) as well. Therefore, Norton concludes that the hope of using this thought experiment, as an argument against the ether theory, appears flawed.

Norton argues that while *Chasing the Light* provides an ineffective argument against the ether theory of light, it is highly effective

[1] Henceforth, the 'propagation of light' is assumed to be in a vacuum.

against emission theories (Norton 2004, 79). The latter theories posit that light always propagates at c with respect to its source of emission. Although Einstein recalls engaging in the thought experiment during high school, before studying emission theories at university, Norton recommends that we situate *Chasing the Light* during Einstein's university period (Norton 2004, 78-79). Norton primarily justifies his interpretation by arguing that concerns (1) and (2) from *Chasing the Light* provide legitimate problems for emission theories, where they failed to do so for ether theory (Norton 2004, 79-80).

Concern (1) from *Chasing the Light*, regarding the lack of sensory experience, is problematic for emission theories because such theories predict that frozen light would be a commonplace observation. That is, if light waves always travel at c with respect to their source of emission, then one would expect an observer to experience frozen light whenever such a source receded from her very rapidly. Since frozen light is not, in fact, a commonplace observation, emission theories would seem to make an incorrect prediction.

Concern (2), regarding the phenomena allowed by Maxwell's equations, is less straightforward in problematizing emission theories because one central aim of emission theories was to replace Maxwell's theory altogether. However, Norton points out that concern (2) remains an issue for emission theories in that any successful emission theory would be required to match the remarkable predictive success of Maxwell's equations. While Maxwell's theory strictly forbids frozen light in static electric and magnetic fields, emission theories allow frozen light in these same fields. Since electrostatics and magnetostatics encompass the most secure and simple predictions of Maxwell's equations, this disagreement poses a greater problem for emission theories. Therefore, Norton contends that concern (2) also poses a legitimate threat to emission theories as a viable means of explaining and predicting light propagation.

Overall, I concede that Norton convincingly argues that *Chasing the Light* challenges the viability of emission theories of light propagation. Specifically, Norton explains how Einstein's concerns (1) and (2) may be truly problematic for such theories. Norton's interpretation is conceptually and historically interesting in that it elucidates potential reasons for Einstein's eventual abandonment of emission theories. If one is willing to be skeptical about Einstein's ability to correctly recall the precise period in which he first thought of *Chasing the Light*, Norton's interpretation is also historically plausible.

IV. An Alternative Interpretation

Despite Norton's formulation of an interesting and plausible interpretation of *Chasing the Light*, there remain reasons to be skeptical of his perspective. My immediate objection to Norton is that he requires us to dispense with Einstein's own testimony regarding the period in which he first conceived of *Chasing the Light*. If one is willing to treat this aspect of Einstein's recollection as unreliable, then why grant integrity to any passage from the thought experiment?

In a debate about the proper interpretation of this source, it seems most appropriate to search for an interpretation that preserves the entire source, rather than to select those specific passages that best support one theory.

I would like to argue that Norton and other commentators use an incomplete interpretation of *Chasing the Light*. I noted previously that commentators struggle with the issue of how the perplexing phenomenon of frozen light relates to Einstein's eventual adoption of special relativity. I contend that the phenomenon of frozen light should not be our point of emphasis, because the greater value of *Chasing the Light* is its elucidation of the problems that arise when we observe light while moving at any speed with respect to the ether. To understand why any motion through the ether is problematic, we ought to presuppose the principle of relativity in the thought experiment.[2]

Recall that on Norton's account, the ether theorist is able to respond to *Chasing the Light* by (1) appealing to the fact that we have never travelled fast enough to observe a frozen light wave, and (2) showing that frozen light is allowed by Maxwell's equations. These responses treat *Chasing the Light* as though it does not presuppose the principle of relativity. If we include the principle of relativity as a prior

[2] Banesh Hoffmann (1982 in Holton and Elkana 1982, pp. 93-97) has previously suggested that Einstein tacitly presumed some form of the principle of relativity when questioning the odd notion of frozen light, but that due to some psychological block he did not apply it more broadly such that *Chasing the Light* could conceptually threaten ether theory.

assumption, we see that focusing solely on the phenomenon of frozen light misses the point. On this modified account, the thought experiment shows that an observer who increases their velocity with respect to the ether will measure the speed of light to be decreasing. Described more formally, we can say that for an observer travelling at velocity v through the ether, their observed speed of light is represented by $c - v = \epsilon$, and therefore $\epsilon < c$ whenever $v > 0$. This is not the same phenomenon as we describe when an observer increases their velocity with respect to another moving body, because ether theory holds the medium through which light propagates to be in a state of absolute rest. Therefore measuring a decreasing value for the speed of light - and eventually motionless light where $v = c$ so that $\epsilon = 0$ - is equivalent to measuring one's own *absolute motion* to be increasing: a clear violation of the principle of relativity.

As I have indicated, Norton does not address how an ether theorist would rebut *Chasing the Light* if we presuppose the principle of relativity in this way. With regards to the above discussion, I do not believe that an ether theorist could effectively respond. Therefore, by (a) taking the principle of relativity as a starting assumption and (b) emphasizing any inertial motion with respect to the ether (including the most extreme case of motion at speed c), this thought experiment becomes a highly effective argument against the notion of the electromagnetic ether.

V. Conceptual and Historical Considerations

Having proposed a novel interpretation of *Chasing the Light*, I want to defend this interpretation as being both at least as interesting and at least as plausible as Norton's account. First, for my interpretation to be interesting, it is crucial not to confuse the principle of relativity with the broader theory of special relativity. If *Chasing the Light* required us to presuppose all of special relativity, it would be a trivial musing that offered no conceptual contribution to the development of the theory, and it would be senseless for Einstein to claim otherwise in the *Autobiographical Notes.* While my interpretation of the thought experiment presupposes the principle of relativity, it does not presume the light postulate. Furthermore, by understanding *Chasing the Light* as a refutation of the ether, it can be seen as preparing Einstein for the adoption of a new theory about the propagation of light. From this perspective, the thought experiment remains an interesting and constructive factor in Einstein's path toward special relativity, even before he considered the possibility of emission theories.

Second, it is entirely plausible that Einstein held the principle of relativity as a background assumption when conceiving of *Chasing the Light* during his high school years, and prior to considering the light postulate. The notion of equivalent inertial reference frames, which underlies the principle of relativity, was present in physics long before Einstein and special relativity in the form of "Galilean relativity" (DiSalle 2006, 28-29). As early as 1632, Galileo proposed that observers aboard a uniformly moving ship could not possibly conduct an experiment that would reveal them to be in motion rather than at rest (Galilei 1632, 186-187). Newton recognized the importance of this Galilean relativity, and even developed it as a "corollary" to his laws of motion such that it would have been an inherent component of subsequent Newtonian physics (DiSalle 2006, 28-29).

This suggestion about Einstein's adherence to Galilean relativity may immediately invoke suspicion. That is, one may ask how Einstein could be expected to have used the central notions of Galilean relativity as stimuli to eventually replace this same theory of spacetime. My answer is that Einstein did not presume all of Galilean relativity, but only those foundational concepts that can be used to define 'inertial frames' and thus allow for the statement and presupposition of the principle of relativity. These concepts can be found in the geometrical structures common to both Galilean and special relativity. The geometrical structures that provide the mathematical analogue for inertial frames are not unique to Minkowski geometry, but are rather properties of all *affine spaces*.[3] Since *affine spaces* underlie both Minkowski geometry as well as the non-relativistic Euclidian geometries used prior to relativity theory, it can be assumed that the notion of inertial frames that is foundational to the principle of relativity was an inherent aspect of the geometry that

[3] 'Minkowski geometry' refers to the geometrical structure used to describe the spacetime of special relativity, which includes mathematical analogs for both the principle of relativity and the light postulate.

Einstein was taught in school.[4] A more formal, detailed treatment for this argument about *affine space* is given in Section VI.

Moreover, Einstein seems to recall his presumption of the principle of relativity when considering his thought experiment. He notes that, "from the very beginning it appeared...intuitively clear that, judged from the standpoint of [a rapidly moving] observer, everything would have to happen according to the same laws as for an observer who, relative to the Earth, was at rest" (Einstein 1949, 53). I contend that the best reading of this particular passage is also the simplest and most literal: Einstein feels strongly that the laws of physics must be the same across all inertial reference frames, so that no observer can determine their *absolute motion*. On this reading, Einstein's intuition appears to be a clear expression of the principle of relativity.

VI. Inertial Frames Before Einstein

In the previous Section, I claimed that the basic notion of equivalent inertial reference frames in physics is common to both Galilean relativity and special relativity. I argued that this commonality from the perspective of physics might be related to the deeper geometrical commonality among different conceptions of relativity: their

[4] I derive this claim from a well-known set of lecture notes by David Malament (2009), in which he explains that Minkowski and non-relativistic Euclidian geometries differ only in the types of metrical structures that they contribute to affine spaces.

formal geometrical descriptions are both based on *affine spaces*. Although the 'Minkowski geometry' that describes special relativity differs from the non-relativistic Euclidian geometry that describes Galilean relativity, these differences result from the different additional metrical structures that each geometry overlays onto *affine spaces*. Therefore, if we can derive a notion of equivalent inertial frames from *affine spaces* alone, without the additional structures of Minkowski geometry, we obtain evidence that important conceptual components of the principle of relativity were widely held and taught in geometry before Einstein considered *Chasing the Light*.

An *affine space* $A = (S, V, +)$ is a triple in which S is a non-empty set of points, V is a 4-dimensional vector space (which provides a means of connecting the points), and $+$ is an associative function from $A \times V$ to A (which provides a notion of addition). Interpreting the points as spacetime points, we can use an *affine space* to model the structure of spacetime that is shared by both Minkowski and Euclidean geometry (Malament 2009). For present purposes, since the physics we are concerned with requires 3 dimensions of space and 1 dimension of time, we need to find some way to construct a foliation of this 4-dimensional *affine space* into hypersurfaces to obtain a representation of an inertial reference frame. Here is how I propose to do so. Let $\sum_s$ be a collection of 3-dimensional hypersurfaces of A indexed by the parameter $S \subseteq \mathbb{R}$. This means that $\sum_s = (S', V', +)$ is a 3-dimensional *affine space*, where S' is a subset of S and V' is a subspace of V. Call such a collection a foliation of A into hypersurfaces if and only if $\cup_{S\subseteq\mathbb{R}} \sum_s = A$.

Let us now interpret one necessary condition on an inertial frame as that it consists in a foliation of A, together with a straight line that intersects each $\sum_s$ exactly once. It is possible to define a concept of a straight line in an *affine space* (Malament 2009). We shall interpret this straight line as indicating the time t for an inertial observer in that frame. When an inertial observer boosts to a different velocity, their frame of reference changes and is transformed from (x, y, z, t) to (x', y', z', t') in our foliation of A. These foliations of A may then describe the inertial frames for either the Galilean spacetime of pre-relativistic physics, or the Minkowski spacetime of special relativity, or some other theory altogether.

Let F be the set of all the foliations of A; let M be a subset of those foliations corresponding to the equivalent inertial frames of Minkowski spacetime, and let G be the subset corresponding to the Galilean inertial frames. Determining whether frames belong to G or M - or some other subset of F - depends on what physical spacetime theory that we choose to overlay onto a foliation of 4-dimensional *affine space*. One example of a theory that overlays additional structure onto *affine space* is the light postulate, which is part of special relativity but not Galilean relativity; this additional structure - implemented by the Lorentz transformations, or by the Minkowski metric - would designate a frame as belonging to M and not G.

However, one does not need all of this additional structure to state the principle of relativity: all we require is a description of inertial frames. Whatever subset of F happens to describe the inertial frames of our theory, we can still state the principle of relativity as the claim, 'The laws of physics are the same in all inertial reference frames'. This statement can be made about any set of foliations of our *affine space*, whether it corresponds to relativistic or pre-relativistic physics. We thus have a precise specification of the meaning of 'inertial frames' that is general enough to state the principle of relativity without presuming the full structure of special relativity.

VII. Further Historical Considerations

Thus far, I have argued that this proposed interpretation of *Chasing the Light* is at least as plausible as that of Norton. I will now provide some final historical evidence to indicate that this interpretation may be more plausible than Norton's account. This claim arises from the observation that Norton's historical narrative admits of a curiosity. If one follows Norton in situating *Chasing the Light* during Einstein's university period, while he was studying emission theories, how can one defend Einstein's blatantly erroneous claim that Maxwell's equations do not allow for frozen light waves? This mistake would appear so obvious to a student of Maxwell's theories that it seems more plausible that a sixteen-year-old Einstein made this error - prior to attending university - while unfamiliar with the equations. Under this chronology, as endorsed by Einstein himself, *Chasing the Light* would have played an important role before he engaged with emission theories. Indeed, the interpretation proposed here suggests that *Chasing the Light* may have been an early motivator for the university-aged Einstein to consider emission theories as a replacement for ether theory.

My claim should not be taken to suggest that Norton's interpretation lacks value. On the contrary, Norton exposes several compelling conceptual issues that *Chasing the Light* would pose for emission theories; a research project that Einstein also eventually abandoned. From a historical perspective, it therefore seems entirely possible that Einstein continued to use *Chasing the Light* as a heuristic by which he interrogated emission theories after discarding ether theory. On this view, Norton's interpretation is compatible in many respects with the interpretation proposed here.

VIII. Conclusion

In sum, there are conceptual and historical reasons for adopting an alternative understanding of *Chasing the Light*. Standard interpretations of *Chasing the Light*, including Norton's position, overemphasize the hypothetical phenomenon of observing frozen light and thereby miss important lessons that can be drawn from the thought experiment. This narrow interpretation contributes to the confusion that is observable among commentators. By presupposing the principle of relativity in *Chasing the Light*, and thereby understanding any change in the speed of light as conceptually problematic, we obtain a clearer argument against the notion of the ether and toward the adoption of the light postulate.

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