higher the yard-arm, the faster the ship travels with the same sail and the same wind?", (8) "Why are round and circular things easier to move than things of other shapes?", (10) "Why is an empty balance easier to move than a weighted one?", (11) "Why are heavy weights more easily carried on rollers than on carts, though the latter's wheels are larger while the circumference of rollers is small?", (26) "Why is it more difficult to carry long timbers on the shoulders by the end than by the middle, provided that the weight is equal in the two cases?" (Diogenes Laertius 1925).

REFERENCES

Aristotle. [1936] 1955. *Minor Works,* with an English translation by W. S. Hett. Cambridge, MA: Harvard University Press/London: William Heinemann.

Arthur, R. T. W. 1999. "On Thought Experiments as *a Priori* Science." *International Studies in the Philosophy of Science* 13 (3): 215–229.

Brown, James R. 1991. *The Laboratory of the Mind: Thought Experiments in the Natural Sciences.* London: Routledge.

Darling, David J. 2004. *The Universal Book of Mathematics: From Abracadabra to Zeno's Paradoxes.* Hoboken, NJ: Wiley.

Diogenes Laertius. 1925. *Lives of the Eminent Philosophers.* Books V and VIII. Translated by Robert Drew Hicks. http://en.wikisource.org/wiki/Lives_of_the_Eminent_Philosophers/Book_V http://en.wikisource.org/wiki/Lives_of_the_Eminent_Philosophers/Book_VIII#Archytas (accessed August 23, 2011).

Drabkin, Israel E. 1950. "Aristotle's Wheel: Notes on the History of a Paradox." *Osiris* 9: 162–198.

Fontenelle, Bernard Le Bovier de. 1717. "Sur la roue d'Aristote." In *Histoire de l'Académie Royale des Sciences Année 1715.* Paris: Imprimerie Royale.

Galilei, Galileo. [1638] 1914. *Dialogues Concerning Two New Sciences.* Translation of *Discorsi e dimostrazioni matematiche, intorno à due nuove scienze,* by Henry Crew and Alfonso de Salvio. New York: Macmillan. www.questia.com/PM.qst?a=o&d=88951396 (accessed August 23, 2011).

Hutton, Charles. 1815. *A Philosophical and Mathematical Dictionary.* New edition. Vol. 2. London.

Koyré, Alexandre. 1968. "Galileo's Treatise 'De Motu Gravium': the Use and Abuse of Imaginary Experiment." In *Metaphysics and Measurement: Essays in Scientific Revolution.* London: Chapman and Hall.

Sorensen, Roy A. 1992. *Thought Experiments.* Oxford: Oxford University Press.

Winter, Thomas N. 2007. "The *Mechanical Problems* in the Corpus of Aristotle." DigitalCommons@University of Nebraska–Lincoln. http://digitalcommons.unl.edu/classicsfacpub/68 (accessed August 23, 2011).

---

7 Chasing the Light

Einstein's Most Famous Thought Experiment

John D. Norton

1. INTRODUCTION

How could we be anything but charmed by the delightful story Einstein tells in his "Autobiographical Notes" of a striking thought he had at the age of sixteen? While recounting the efforts that led to the special theory of relativity, he recalled

> a paradox upon which I had already hit at the age of sixteen: 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 an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, neither on the basis of experience nor according to Maxwell's equations. From the very beginning it appeared to me intuitively 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 should the first observer know or be able to determine, that he is in a state of fast uniform motion?
>
> One sees in this paradox the germ of the special relativity theory is already contained. (Einstein 1951, 52–53 [1979, 48–51])

Einstein is celebrated for devising penetrating thought experiments and here we are offered a thought experiment that contains the germ of his great discovery. Yet the thought experiment is so simple that it could arise in the playful musings of a sixteen year old. It is little wonder that this thought experiment is widely cited and praised.

All this is deceptive. The thought experiment is unlike Einstein's many other thought experiments in two ways. First and foremost, unlike them, it is entirely unclear how this thought experiment works. Upon encountering the thought experiment, most readers likely find the imagery quite vivid and even seductive. But they should be, and typically will be, left with a sense of incomplete understanding. Just why, they should ask, is the frozen light of this thought experiment problematic? The question is unlikely to be pursued. Most readers expect Einstein's thought to be abstruse and a failure of understanding to be the reader's fault. That may often be the case, but in this instance, the opacity is no fault of readers. It is not at all clear how the thought experiment works. As will be recounted in Section 2 below, if we read the thought experiment as securing a fatal defect of the then dominant ether-based theories of electrodynamics, it fails. This is the "physical problem" to be addressed here.

Readers seeking help in understanding this curious failure will find little help in the secondary literature. As I shall explain in Section 3, that literature almost never acknowledges the problem. It may simply paraphrase Einstein's text, perhaps hoping the reader will penetrate the thought experiment in a way the author did not. Or it may discourage a reader from seeking cogent explication by praising Einstein's prescient intuition. We are to admire his ability to see fragments of the relativity theory to come in what Einstein (1956, 10) elsewhere called a "child-like thought experiment," but we lesser minds should not expect to understand how he saw it. And worse, an author may feign understanding and give the thought experiment an explication that connects poorly with Einstein's text. The unfortunate reader now has two problems: to understand Einstein's text and to understand the explication!

Second, there is a "historical problem," as I shall call it, to be laid out in Section 4. The thought experiment was conceived by Einstein in late 1895–early 1896 and involves a confident assertion of what Maxwell's equations permit. Yet the young Einstein was not to learn Maxwell's theory until around 1898. Is Einstein merely describing a thought experiment from 1895–1896? Or is the thought experiment now also intermingled with later analyses?

My solution to both physical and historical problems is to suggest that Einstein's thought experimenting with frozen light persisted well into his researches that lead up to the 1905 special theory of relativity. Versions of the thought experiment were conducted after Einstein had mastered Maxwell's equation. During this time, Einstein gave long and serious consideration to emission theories of light. In them, the speed of a light beam is c, not with respect to the ether, but with respect to the emitter. These emission theories were Einstein's best and perhaps only hope of realizing a principle of relativity in electrodynamics, prior to his recognition that these efforts would require a new theory of space and time. I will propose that Einstein's "Autobiographical Notes" version of the thought experiment recounts powerful reasons for abandoning emission theories, if in abbreviated form. These theories and some of Einstein's discussion of them will be described in Section 5. The rereading of Einstein's thought experiment as providing objections to emission theories will be given in the concluding Section 6. The thought experiment is then seen to succeed in offering reasons as clear and cogent as in any of Einstein's other thought experiments. It has the added benefit of clarifying cryptic remarks Einstein made elsewhere concerning his discarding of emission theories.

In what follows, I will take the above-quoted presentation of the thought experiment from "Autobiographical Notes" as the canonical version of the thought experiment. My purpose here is to explicate this version of the thought experiment. While I will discuss reports of other versions below, this one is both its best-known exposition and, presumably, the one that Einstein drafted most cautiously. It was written for a text that Einstein knew would be his official autobiography.

2. PHYSICAL PROBLEM

The thought experiment calls upon some elementary physics of light waves from Maxwell's electrodynamics. In that theory, space is filled with an all-pervading medium, the ether. Electric and magnetic fields arise as states of that ether. A propagating light wave is a sinusoidal electric and magnetic field whose waveform propagates at c, the speed of light. In these essentials, the theory's account of propagating light differs little from one of waves propagating over water. The ether corresponds to the water, and the electric and magnetic field strengths correspond to the displacement of the water's surface into peaks and troughs.

Einstein's thought is simple. If he were somehow to chase after that propagating waveform at c, he would catch the wave and move with it, much as a surfer catches a water wave. He would find a frozen light wave. But that possibility, Einstein declares, is untenable for three reasons, and in that failure he finds the germ of the special theory of relativity.

What remains unclear is just *how* Einstein's three reasons establish that the frozen waveform is untenable and thereby create difficulties for the nineteenth-century account of light. His target, presumably, is the ether state of rest around which Maxwell's electrodynamics is constructed. Yet an ether theorist can readily defeat each of the three reasons Einstein lists. To see how they are defeated, let us dissect Einstein's text to expose the three reasons and juxtapose an ether theorist's natural response (see Table 7.1).

Once the ease of the ether theorist's response is seen, Einstein's thought experiment becomes more than puzzling. It seems to rest on elementary oversights unworthy of an Einstein. He appears to demand experiences that we do not have simply because we are moving slowly. We do not see frozen light since we are not moving at c. Einstein also seems to have become an inept theorist. He disallows the compatibility of frozen light with Maxwell's theory, when a two-line computation in the theory—given in my endnote—shows that a rapidly moving observer would be surrounded by frozen light. Finally, Einstein's concluding rhetorical question is answered directly by an ether theorist. When you find light frozen, you are moving very fast.

Table 7.1 An Ether Theorist's Response to Einstein

	Einstein wrote:	*The Ether Theorist's Response*
	"I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, . . ."	
1	" . . . neither on the basis of experience . . ."	We do not experience frozen light since we are not moving at c through the ether. If we were moving that fast through the ether, we would experience frozen light.
2	" . . . nor according to Maxwell's equations."	Not so. A very short calculation[1] shows that Maxwell's equations predict that light becomes frozen for observers moving at c through the ether.
	"From the very beginning it appeared to me intuitively 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."	
3	"For how should the first observer know or be able to determine, that he is in a state of fast uniform motion?"	Observers know they are moving rapidly with respect to the ether simply because light has become frozen. Analogously, surfers know they are moving since their position on the wave does not change.

3. COMMENTARIES

We should give Einstein the benefit of the doubt when he writes something that seems trivially and fatally wrong. However, that charity should not extend to a failure to recognize that we face a problem in reconstructing Einstein's intentions. That failure is widespread among commentaries written on Einstein's thought experiment. While I am far from having surveyed all such commentaries,[2] my small explorations have turned up only a tiny fraction of commentaries that admit to a problem.

Perhaps the clearest is Adolf Grünbaum's (1973, 371–375). He rehearses some of the concerns I express above and concludes memorably:[3]

> In view of the presumably flimsy character of the appeal to experience and of the redundancy of (2) with (3) among the reasons given by Einstein, we are pretty much left with his intuitive confidence in the principle of relativity as the basis for his assumption [light is the fastest signal *in vacuo*]. (1973, 374–375)

Einstein's former collaborator, Banesh Hoffmann (1982, 94–97), lays out the objection to Einstein's second reason. He recapitulates the easy demonstration in a non-relativistic spacetime of the possibility of frozen light, but he finds a prescience in Einstein's psychological reaction to the thought experiment.[4] Olivier Darrigol (1996, 289–290) is less eager to exculpate Einstein. He judges Einstein's reminiscence "either false or misdated" and concludes: "We should therefore regard the widespread belief that Einstein had an inborn trust in the relativity principle as a myth. In fact, he originally believed in Maxwell's electromagnetic ether." Citing Darrigol's analysis, Marc Lange (2002, 201) reviews the difficulties of reading Einstein's thought experiment as a prompt in a list of discussion questions. He asks, provocatively, "Is Einstein's famous argument from 'riding on a beam of light' flawed?" but does not apparently take a stand himself.

These critical reactions are exceptional. Virtually all commentaries fail to acknowledge that something appears to be amiss. The most benign of these, such as Martinez (2009, 213–214), merely report Einstein's remarks without attempting elucidation. The exposition may even be a rather close paraphrase. Whitrow[5] says that

> the beam of light would then appear as a spatially oscillating electromagnetic field at rest. But such a concept was unknown to physics and at variance with Maxwell's theory. (1973, 11)

There is no further explication, so the reader is apparently intended to understand these remarks directly. Fortunately, some reports flag to the reader that there might be a problem. Immediately after quoting Einstein's text, Bergia[6] concedes:

> We deliberately restrain ourselves from touching upon the point of logical internal consistency in this passage (Grunbaum); we rather call attention to the "intuitive" conclusion it leads to: as a spatially oscillatory field at rest "does not make sense," no observer, i.e. no material body, can reach the velocity *c*. (1979, 84)

Other authors are less ready to admit the problem as they struggle to clarify Einstein's remarks. Holton finds Einstein's narrative to have

> its exact parallel in the 1905 paper, in the conceptual leap from a simple experiment (indeed, also a kind of *Gedanken* experiment—the relative motion of conductor and magnet) to the general principle from which the content of relativity theory will derive. (1973, 293)

Here Holton refers to the magnet and conductor thought experiment that initiates Einstein's famous "On the Electrodynamics of Moving Bodies" (Einstein 1905), in which he first presents special relativity. That thought experiment derives from a fact in ether-based electrodynamics. A magnet at rest in the ether is surrounded by a magnetic field. A magnet moving in the ether is surrounded by a magnetic field and an induced electric field, arising through the magnet's motion. One might expect this electric field to be an experimentally detectible sign of the magnet's motion in the ether, for one can detect the electric field from its ability to create a measurable electric current in a conductor in the vicinity of the magnet. Yet, Einstein reported, a curious combination of effects leads to the same current in the conductor no matter whether the magnet is at rest in the ether or moving in it.[7]

The similarity, Holton continues, persists in the details of the two experiments. They are

> physically of precisely the same kind: in one case the question concerns the electric and magnetic fields a moving observer finds to be associated with a light beam; in the other case, it concerns the electric and magnetic fields experienced by a moving conductor; and the solutions in both cases follow from the same transformation equations. (1973, 293)

While there are some similarities here, they do not extend to the point at issue. Einstein's inference in the case of the magnet and conductor thought experiment is clear and unequivocal. Ether theories of electromagnetism are positing a state of rest that is, in this case, mysteriously obscured from detection. Einstein's inference in the case of the chasing a light beam thought experiment is apparently flawed; it is not clear how it creates a problem for ether-based electrodynamics.

In the course of the nineteenth century, ether-drift experiments had sought to measure the slight shift in the speed of light that ought to result from the earth's motion in the ether. It later became a much-celebrated fact that no effect was measured by these experiments. Miller calls on this as a partial explanation of Einstein's remarks:

> At sixteen, Einstein must have known of some, or perhaps all, of the famous ether-drift experiments, thus accounting for the comment: "However there seems to be no such thing . . . on the basis of experience." (1981, 169)

The difficulty with this reading is that Einstein's "no such thing" refers directly to "an electromagnetic field at rest though spatially oscillating" and there is quite some gap to be closed between that and the very slightly slowed or sped up light that eluded the terrestrial ether-drift experiments.

Miller (1981, 169) also repeatedly points to Einstein's wording "intuitively clear" in relation to his early conviction in the principle of relativity.

Other authors go further and emphasize Einstein's prescient intuition in celebratory tones, perhaps intending to forestall a demand for explanation of Einstein's reasoning. Sartori praises Einstein's "inspired intuition":

> The seed of the theory of relativity had evidently been planted when Einstein was only sixteen years old! The idea that light has the same speed in all inertial frames, so difficult for an ordinary mind to grasp, was a quite natural one for Einstein. He was prepared to accept it even without strong experimental evidence. (1996, 53–54)

Yet other authors struggle to make Einstein's discomfort with frozen light credible through ornamenting Einstein's account with picturesque details. Bernstein attempts to clarify Einstein's dismissal of frozen light by remarking:

> It would be like coming across a pond which had a wavy surface but the waves did not move. This would certainly appear "paradoxical." (2006, 62)

While the image of a pond with frozen waves is striking, it is not the one that would match Einstein's construction. One needs to add that Einstein is chasing after the waves. Then it would be trivial that an Einstein chasing the waves on the water's surface would find frozen waves. They would not appear paradoxical. More inventively, Schwartz and McGuiness (1979, 75–76) locate the puzzle in the fact that an Einstein, traveling with light, would be unable to see his reflection in a hand-held mirror included in the illustrations. While that would be true, it is not at all clear from his text that this is just what troubled Einstein in the thought experiment.

Finally, in an apparent eagerness to provide a seamless account, an author may end up misstating the physics. Kaku relates how Einstein found that his aversion to frozen light was vindicated when he later learned Maxwell's theory:

> When Einstein finally learned Maxwell's equations, he could answer the question that was continually on his mind. As he suspected, he found that there were no solutions of Maxwell's equations in which light was frozen in time. But then he discovered more. To his surprise, he found that in Maxwell's theory, light beams always traveled at the same velocity, no matter how fast you moved. (2004, 45)

This is supposedly what Einstein learned as a student at the Zurich Polytechnic, where he completed his studies in 1900, well before the formulation of the special theory of relativity. Yet the results described are precisely what is *not* to be found in the ether-based Maxwell theory Einstein would then have learned. That theory allows light to slow and be frozen in the frame of reference of a sufficiently rapidly moving observer. The results Kaku describes are the ones that obtain in Maxwell's theory only after it is ported to the space and time of Einstein's special theory of relativity.

In sum, even though Einstein's "Autobiographical Notes" account appears to relate a sequence of inferences readers can follow, the celebrated thought experiment is poorly understood. Very few authors admit this directly. Most feign understanding and the positive proposals offered connect poorly with each other and with Einstein's text.

4. HISTORICAL PROBLEM

When a report by Einstein creates this much confusion, we need to proceed carefully. First, we need to be secure in our sources. The canonical text of Einstein's "Autobiographical Notes" contains an oddity. It indicates that he found the paradox at age sixteen. Since he was born on March 14, 1879, that coincides with the year March 1895–March 1896. Another report (cited below) locates the thought experiment in Einstein's school year at Aarau, which lasted from late October 1895 to September 1896. These dates coincide well enough to place the thought experiment in late 1895 to early 1896.

The historical problem this creates is that the "Autobiographical Notes" narrative has an essential role for Maxwell's equations. Yet we know from other reports that Einstein did not learn Maxwell's theory until his university studies around 1898 (see Stachel et al. 1987, 223–235).

We have two other accounts of the thought experiment. Neither mentions Maxwell's equations and both are distinctive in emphasizing the hesitancy of Einstein's conclusion. In a reminiscence of his year at the gymnasium in Aarau, Einstein wrote:

> During this year in Aarau the following question came to me: if one chases a light wave with the speed of light, then one would have before one a time independent wave field. But such a thing appears not to exist! This was the first child-like thought experiment related to the special theory of relativity. Discovery is not a work of logical thought, even if the final product is bound in logical form. (1956, 10)

Einstein admits the thought experiment was "child-like" and his concluding sentence seems to warn us that we should not expect the logic of the thought experiment to be fully evident.

The second account comes from the gestalt psychologist Max Wertheimer, who interviewed Einstein in 1916 as part of Wertheimer's research in psychology. His report of the interview was published posthumously in 1945 in his volume *Productive Thinking*:[8]

> The problem began when Einstein was sixteen years old, a pupil in the Gymnasium (Aarau, Kantonschule). . . .
>
> The process started in a way that was not very clear, and is therefore difficult to describe—in a certain state of being puzzled. First came such questions as: What if one were to run after a ray of light? What if one were riding on the beam? If one were to run after a ray of light as it travels, would its velocity thereby be decreased? If one were to run fast enough, would it no longer move at all? . . . [W's ellipses] To young Einstein this seemed strange.
>
> . . . When I asked him whether, during this period, he had already had some idea of the constancy of light velocity, independent of the movement of the reference system, Einstein answered decidedly: "No, it was just curiosity. That the velocity of light could differ depending upon the movement of the observer was somehow characterized by doubt. Later developments increased that doubt." (Wertheimer 1959, 214–215)

Once again, Maxwell's equations have no role and the certainty of the "Autobiographical Notes" account is replaced by mere discomfort, puzzlement, and doubt.

The historical problem is to reconcile these differences in the accounts of the thought experiment. The solution, I propose, is straightforward. Einstein may have first hit upon the idea of chasing light as a sixteen year old. However the thought experiment evolved as his researches evolved. In its earliest form, it was, in major part, the precocious imaginings of an inventive sixteen year old, driven as much by intuition as reason. This early form of the thought experiment is reported by Wertheimer and by Einstein's second report. Einstein's "Autobiographical Notes" account, however, reports a later development of the thought experiment. It is a version undertaken when Einstein had some command of Maxwell's equations and, through the thought experiment, arrives at results more definite than the mere puzzlement and doubt of the sixteen year old.

While this may solve the historical problem, it only deepens the physical problem. For if "Autobiographical Notes" reports a thought experiment undertaken by an older, more knowledgeable and more capable Einstein, how could he get it so wrong? My solution to this deepened physical problem is that Einstein is not aiming the thought experiment against ether theories of electromagnetism, but against a different sort of theory.

5. EMISSION THEORIES AND THEIR PROBLEMS

Some years before Einstein sent his completed special theory of relativity to the journal *Annalen der Physik*, he became convinced that the principle of relativity must hold for electrodynamic processes, even if Maxwell's theory did not allow it. The thought experiment that played a decisive role in forming this conviction was his magnet and conductor thought experiment. That thought experiment showed him that what you could measure in electrodynamics did not distinguish uniform motion from rest in the ether. Yet Maxwell's theory treated the two cases very differently. Somehow, Einstein concluded, Maxwell's theory must be changed so that the resulting theory conforms with the principle of relativity.

We can see most simply the sort of changes needed if we consider light, which is, in Maxwell's theory, just a propagation of waves in the electric and magnetic fields.

In Maxwell's theory, a light wave in a vacuum always propagates at the same speed, c, with respect to the ether. So measuring the speed of a light beam gives observers an easy way to determine their motion in the ether. If they find the light to move at c, the observers are at rest in the ether. If they find the light frozen, they are moving at c in the ether. Since observers can determine their absolute motion, the theory violates the principle of relativity.

The alternative theory that Einstein began to pursue was an "emission theory." In such a theory, the speed of light *in vacuo* is still c. But it is not c with respect to the ether; it is c *with respect to the source* that emits the light. In such a theory, observing the speed of a light beam tells observers nothing about their absolute motion. It only reveals their motion with respect to the source that emitted the light. If they find the beam to propagate at c, the observers are at rest with respect to the emitter. If they find the beam to be frozen, they are fleeing from the source at c. All the intermediate cases are possible too. In general, observers can only ascertain their relative velocity with respect to the source.

A distinctive property of this emission theory is that there is no single velocity of light; the velocity will vary according to the velocity of the emitter.

All this just pertains to one part of electrodynamic theory, the propagation of light. In order to mount a complete emission theory in which the principle of relativity holds, Einstein would need to propagate these sorts of changes throughout the complete theory. One might imagine that such modification would be extremely hard to carry out. It turns out, however, that one can make a lot of progress very quickly. On the basis of numerous clues that Einstein left in later writings, I believe it is possible to discern quite credible candidates for the theories or theory fragments Einstein developed; and these have been reconstructed in some detail in Norton (2004, §§2–3).[9]

These efforts, I believe, would initially have seemed quite promising. That fact presumably encouraged Einstein to persist in his efforts to find a serviceable emission theory. Einstein persisted for years, as he recalled in a 1920 recollection:

> The difficulty to be overcome lay in the constancy of the velocity of light in a vacuum, which I first believed had to be given up. Only after years of [*jahrelang*] groping did I notice that the difficulty lay in the arbitrariness of basic kinematical concepts. (Einstein [1920] 2002, 280)

Eventually Einstein did give up on an emission theory. There is an indication that the struggle with the emission theory was long and arduous. After he had proposed his special theory of relativity, Einstein was asked repeatedly whether an emission theory was viable. Einstein's correspondence after 1905 and some manuscript sources contain a wealth of objections that reflect serious probing of the possibility of an emission theory and from many perspectives.

These many objections by Einstein are collected and discussed in Norton (2004, §4). For what follows, two of these many objections are important:

- A serviceable emission theory cannot characterize light waves solely by intensity, color, and polarization, but would need to add a velocity property, which light is known not to possess.
- A serviceable emission theory cannot be formulated in terms of differential equations.

The second objection means that the theory cannot look like a local field theory of the type of Maxwell's theory. In such a theory, the laws are expressed by relations that hold at one point in space and time. These differential equations relate the rate of change in space and time of the fields at that point to the field magnitudes at that point. Once one knows these rates of change, one can find how the fields change as one moves to neighboring points, and from this information piece together the disposition of the fields throughout space and time.

If one is unfamiliar with the details of electrodynamic theory, it will be entirely unclear how these two objections pose problems for an emission theory. One might suppose these details will be obvious to an expert. However, even if one knows some electrodynamic theory, the working of the objection remains unclear. Why should the fact that light has only the properties of intensity, color, and polarization be a problem? And how can one show that no emission theory at all can be formulated in terms of differential equations?

6. THE THOUGHT EXPERIMENT AS AN OBJECTION TO EMISSION THEORIES

Einstein's chasing light thought experiment stayed with him after its initial conception, when he was sixteen years old. It remained in his repertoire of important test cases after 1898, when he had learned the details of Maxwell's theory. In this later period, it did not provide a cogent objection to ether-based theories of electrodynamics. Rather, I propose, it provided powerful and devastating objections to the emission theories, whose exploration and rejection figured essentially in Einstein's researches prior to his 1905 special theory of relativity. It is this, I suggest, that merited inclusion of the thought experiment in Einstein's "Autobiographical Notes" and in a form that included invocation of Maxwell's equations.

In the thought experiment, Einstein offered three objections to frozen light. They fail as objections to an ether-based electrodynamics. An emission theory also allows light to slow when an observer chases after it and to freeze if the pursuit is fast enough. If we read Einstein's objections as leveled against an emission theory of light, they succeed, forcefully.

" . . . on the basis of experience . . ."

The first objection is that we do not experience frozen light. That objection has little force against an ether theory since it merely reflects the fact that we are not moving at c in the ether. In an emission theory, light emitted by a body receding from us propagates slower than c. The speed of recession of the source is subtracted from c to find the speed we will measure. In the extreme case, if the source recedes from us at c, we will find the light emitted by the source to be frozen. As this moving source passes through space, it paints a frozen light wave across space. The universe is filled with many luminous bodies. All it takes is for there to be *just one* light source moving at or near c with respect to us for our space to be painted with frozen light. That is a firm prediction of the emission theory. Yet we have never experienced such a thing. An emission theory can only survive, then, if we make the dubious assumption that no fast-moving luminous bodies have passed through our corner of space—not even one. This is the first failure of an emission theory.[10]

" . . . according to Maxwell's equations . . ."

The second objection is that Maxwell's equations forbid frozen light. One might think that Maxwell's equations have no place in an emission theory, for the emission theory replaces them with a new theory. That is not entirely correct. Maxwell's theory remains the crowning triumph of nineteenth-century physics. It enjoyed massive experimental support and the import of those experiments cannot be undone. A new theory of electrodynamics could not dispense with Maxwell's theory entirely. The new theory can only deviate from it in realms in which Maxwell's theory has not been thoroughly tested. The realm in which the theory has been most thoroughly tested is that of electric and magnetic fields that do not change with time, electrostatics and magnetostatics. Whatever else a new theory might change, this part would have to remain unchanged and must be duplicated within the new theory.

This most secure part of Maxwell's theory prohibits frozen waveforms in a vacuum built out of electric and magnetic fields. It only allows combinations of static fields that dilute in space by the familiar inverse square law. Yet an emission theory, Einstein now saw, must allow the static sinusoidal curves of frozen light in every inertial frame of reference. That is, an emission theory must conflict with that part of Maxwell's theory that we can be sure will survive. This is the second failure of an emission theory.

" . . . a state of fast uniform motion . . ."

Finally, Einstein asks how observers finding frozen light can determine that they are in a state of rapid uniform motion. It is a rhetorical question and Einstein leaves it to readers to fill in the details. Those details can only be recovered if we recreate the background presumed by the rhetorical question. In the context of an emission theory, the state of rapid motion mentioned can only mean rapid motion *with respect to the light source.* The theory has been devised so that there is no absolute motion.

Determining this motion with respect to the source, I will now argue, is essential if the emission theory is to function as a serviceable theory, supporting predictions of future states. Einstein's suggestion is, I believe, that we cannot find this velocity from the instantaneous state of the wave and that leads to the failure of the theory as a predictive system.

To see the problem, recall how Maxwell's theory is used to make predictions. We take the electric and magnetic fields in space at one moment. Through Maxwell's equations, this instantaneous state of the fields then fixes their time rates of change. From these time rates of change, we infer the future states of the fields a moment later, and so on for the whole future of the fields.

A similar sort of analysis turns out to fail for an emission theory. Einstein's chasing light thought experiment provides a simple case of the failure. Our initial state is a sinusoidal wave of fields spread through space. From that initial state alone, we cannot tell if the fields belong to a wave propagating past us at high speed, or if they belong to a wave frozen in space that fails to propagate at all. If we cannot distinguish the cases, we cannot predict what will happen next. To know which case is before us, we need also to know whether the wave was produced by a source that is at rest with respect to us; then we have a propagating wave. Or was it, we must ask, produced by a source receding at c from us; then we have a wave frozen in time.

To answer, we need to know our velocity with respect to the source. Einstein reports his presumption that the same laws hold for rapidly moving observers as for those on earth. That means that we cannot resort to any absolute velocity to help decide which case is before us. Our velocity with respect to the source must somehow be recovered from properties of the instantaneous state of the wave.

At this point, Einstein's initially cryptic objection to an emission theory reported elsewhere becomes decisive. The intrinsic properties of light comprise only intensity, color, and polarization, but *not* a velocity property. That is, there is no way to use the instantaneous properties of the fields to determine how they will develop in time. Is the waveform frozen in time? It is propagating rapidly? No local determination of its instantaneous properties can tell us.[11]

Why is that such a troubling outcome? In modern terms, it is a failure of determinism, that is, a failure of the present state of things to determine the future. We know from elsewhere that failures of determinism troubled Einstein greatly. He followed the nineteenth-century tradition of equating causation with determinism. The indeterminism of modern quantum theory was initially regarded as a failure of causation and this dire way of thinking of the failure would have played some part in Einstein's celebrated complaint about quantum theory: that he could not believe that God played dice with the universe. The equation of determinism and causation is expressed rather clearly by Einstein's statement in a 1950 speech that

> the laws of the external world were also taken to be complete, in the following sense: If the state of the objects is completely given at a certain time, then their state at any other time is completely determined by the laws of nature. This is just what we mean when we speak of 'causality.' Such was approximately the framework of the physical thinking a hundred years ago. ([1950] 2005)

Here is the third failure of emission theories. They cannot be formulated in a way that the present state determines the next and all future states. Emission theories contradict causality and cannot be used for prediction. A formulation of an emission theory must be global in the sense that it must keep track of how each wave field was created.

This third failure can be expressed in a more succinct way. Maxwell's theory is specified by differential equations through which the rates of change of the fields are derived from the instantaneous states of the fields. Einstein had now concluded that an emission theory could not be formulated in this way. Here now is an explanation of Einstein's other cryptic objection to emission theories: that they could not be formulated in terms of differential equations.

The third objection of Einstein's thought experiment turns out to be an abbreviated complaint that emission theories will be defective causally, in the nineteenth-century sense of the term, and unable to make predictions of future states from present states. This reading of the thought experiment enables us also to make sense of two of Einstein's otherwise cryptic remarks on emission theories made elsewhere.[12]

We can summarize the reading proposed in a table analogous to the one given in Section 2 (see Table 7.2).

Table 7.2 Einstein's Approach Contrasted to an Emission Theory

	Einstein wrote:	*Interpretation in an Emission Theory*
	"I should observe such a beam of light as an electromagnetic field at rest though spatially oscillating. There seems to be no such thing, however, . . ."	
1	" . . . neither on the basis of experience . . ."	In an emission theory, we would expect to experience frozen light since any rapidly receding light source paints a frozen waveform across space.
2	" . . . nor according to Maxwell's equations."	An emission theory must agree at least with the electrostatic and magnetostatic parts of Maxwell's theory. Those parts prohibit sinusoidal, static fields in empty space.
	"From the very beginning it appeared to me intuitively 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."	In an emission theory, the observer cannot call upon an absolute velocity to answer the rhetorical question Einstein poses next.
3	"For how should the first observer know or be able to determine, that he is in a state of fast uniform motion?"	Given the instantaneous state of a wave, in an emission theory one needs to know one's state of motion with respect to the emitter to know whether the wave will propagate or not. That velocity is not encoded in the instantaneous state of the waveform, so an emission theory is indeterministic and cannot be formulated in terms of differential equations.

NOTES

1. In Maxwell's theory, a propagating plane lightwave of wavelength λ and frequency v can be given by the two sinusoidal fields $\mathbf{E} = \mathbf{E}_0 \sin 2\pi\,(x/\lambda - vt)$ and $\mathbf{H} = \mathbf{H}_0 \sin 2\pi\,(x/\lambda - vt)$, where **E** and **H** are the electric and magnetic field strengths and x and t are the usual space and time coordinates adapted to the ether frame of rest. If we transform to a frame moving at c in the +x direction of propagation of the wave, the new coordinates X, T adapted to the moving frame are related to the original ether frame coordinates by $X = x - ct$ and $T = t$. Since $c = \lambda v$, we have $x/\lambda - vt = (x-ct)/\lambda$. Hence in the new frame, the transformed fields are $\mathbf{E} = \mathbf{E}_0 \sin 2\pi\,(x-ct)/\lambda = \mathbf{E}_0 \sin 2\pi X/\lambda$ and

$H = H_0 \sin 2\pi (x-ct)/\lambda = H_0 \sin 2\pi X/\lambda$. These transformed waves are independent of the frame time T. They are frozen. (The field strengths E and H transform invariantly in Newtonian space and time.)

2. No doubt my survey has missed many writers and I apologize to those I missed. However, my sample was large enough for me to be confident that the population as a whole fails overwhelmingly to admit that reading Einstein's text is problematic.
3. Grünbaum's reasons (2) and (3) mentioned in his text agree fairly well with reasons 2 and 3 of my table.
4. "[I]nnovation in science is often a triumph of intuition over logic." Hoffmann proposes that Einstein could not have considered seriously the classical result that light will be slowed relative to an observer who chases after it, for this admissibility of slowed light would eventually have forced the idea on Einstein of frozen light. Hoffmann suggests: "Having sensed the existence of a profound paradox, he may have experienced a psychological blocking that prevented him from giving serious consideration to sluggish light." While Hoffmann's efforts to elucidate Einstein's remarks are commendable, they are obscure in that the only paradox Hoffmann recovers is a psychological sense of discomfort in Einstein. (Both quotes from Hoffman 1982, 97.)
5. The text is derived from a BBC radio broadcast in 1967 and this portion of it was spoken by Whitrow as part of a dialog.
6. Presumably Adolf Grünbaum is intended in the following quote. Bergia's bibliography (1979, 88) contains a reference to Grunbaum, A., "The special theory of relativity" in *An Introduction to the Theory of Relativity*, edited by W. G. V. Rosser (London: Butterworths, 1964). There is no Grünbaum text in my copy of this volume. Rosser is the entire volume's author, not editor.
7. For elaboration on Einstein's magnet and conductor thought experiment, see Norton (Forthcoming).
8. We can have some confidence in Wertheimer's narrative. It relates Einstein's recollections in 1916, some twenty years after the event. Einstein's own two narratives are written forty and fifty years after the event. Wertheimer also solicited Einstein's appraisal of the chapter in draft and Einstein replied that he found it "on the whole good." See Norton (2004, 77, fn 31) for further details of Einstein and Wertheimer's correspondence and for my suggestion that reading Wertheimer's draft in 1943 may have instigated Einstein's recounting of the thought experiment in his 1946 drafting of "Autobiographical Notes."
9. These efforts proceed from two ideas. First, as Einstein learned from the magnet and conductor thought experiment, one should allow that electric and magnetic field quantities may not transform invariantly under changes of inertial frame. A pure magnetic field may transform into a combination of magnetic and electric fields. Second was an idea later developed by Ritz. Maxwell's theory can be re-expressed in terms of retarded potentials. In this approach electromagnetic quantities at some point in space and time are assembled from all the electromagnetic effects that propagate to that point from other source charges. The rule used in assembling those effects is that they propagate at c in the ether. Ritz's theory sought conformity with the principle of relativity merely by adjusting this rule. Electromagnetic effects are now assumed to propagate at c with respect to the motion of the source charge.
10. I have found only one other author who considers the possibility that this first objection may have been leveled by Einstein against some sort of emission theory of light: Grünbaum (1973, 373).

11. Einstein's demand for this velocity property is not unreasonable. A simple one-dimensional Klein Gordon field ϕ satisfies the field equation $[(\partial/\partial t)^2-(\partial/\partial x)^2-m^2]\,\phi = 0$. Its plane wave solutions are $\phi = \exp i\,(\omega t-kx)$, where the frequency ω and wave number k satisfy $m^2 = k^2-\omega^2$.

    Since ω and k are related to the speed of the wave v by $v = \omega/k$, it follows that the speed of the wave is fixed by the wave number according to $v = (1-m^2/k^2)^{1/2}$. The wave number k provides the velocity property Einstein sought. The special case of a frozen wave arises when the wave number $k = m$. If one finds a wave whose instantaneous state is $k = m$, then it must be frozen. An analogous analysis fails for light since does it not have a non-zero characteristic parameter m.
12. See Norton (2004, §5) for further discussion.

REFERENCES

Bergia, Silvio. 1979. "Einstein and the Birth of Special Relativity." In *Einstein: A Centenary Volume,* edited by A. P. French, 65–89. Cambridge, MA: Harvard University Press.

Bernstein, Jeremy. 2006. *Secrets of the Old One: Einstein, 1905.* Springer/Copernicus Books.

Darrigol, Olivier. 1996. "The Electrodynamic Origins of Relativity Theory." *Historical Studies in the Physical and Biological Sciences* 26: 241–312.

Einstein, Albert. 1905. "Zur Electrodynamik bewegter Körper." *Annalen der Physik* 17: 891–921.

———. [1920] 2002. "Fundamental Ideas and Methods of the Theory of Relativity, Presented in Their Development." Doc. 31 in *The Collected Papers of Albert Einstein. Volume 7: The Berlin Years: Writings, 1918–1921,* edited by Michel Janssen et al. Princeton, NJ: Princeton University Press.

———. [1950] 2005. "Physics, Philosophy, and Scientific Progress." (International Congress of Surgeons, Cleveland, Ohio, 1950). *Physics Today,* June: 46–48.

———. 1951. "Autobiographical Notes." In *Albert Einstein: Philosopher-Scientist.* 2nd edition. Edited by P. A. Schilpp, 2–95. New York: Tudor Publishing. Reprinted with a correction as *Autobiographical Notes.* 1979. La Salle and Chicago: Open Court.

———. 1956. "Autobiographische Skizze." In *Helle Zeit—Dunkle Zeit,* edited by Carl Seelig, 9–18. Zurich: Europa Verlag.

Grünbaum, Adolf. 1973. "Philosophical Foundations of the Special Theory of Relativity, and Their Bearing on Its History." In *Philosophical Problems of Space and Time.* 2nd edition, 341–409. Dordrecht: Reidel.

Hoffmann, Banesh. 1982. "Some Einstein Anomalies." In *Albert Einstein: Historical and Cultural Perspectives,* edited by G. Holton and Y. Elkana, 91–105. Princeton, NJ: Princeton University Press.

Holton, Gerald. 1973. "Einstein, Michelson and the 'Crucial' Experiment." In *Thematic Origins of Scientific Thought: Kepler to Einstein,* 261–352. Cambridge, MA: Harvard University Press.

Kaku, Michio. 2004. *Einstein's Cosmos: How Einstein's Vision Transformed Our Understanding of Space and Time.* New York: W. W. Norton/Atlas Books.

Lange, Marc. 2002. *An Introduction to the Philosophy of Physics: Locality, Fields, Energy, and Mass.* Malden, MA: Blackwell.

Martinez, Alberto. 2009. *Kinematics: The Lost Origins of Einstein's Relativity.* Baltimore: Johns Hopkins University Press.

Miller, Arthur I. 1981. *Albert Einstein's Special Theory of Relativity*. Reading, MA: Addison-Wesley.

Norton, John D. 2004. "Einstein's Investigations of Galilean Covariant Electrodynamics prior to 1905." *Archive for History of Exact Sciences* 59: 45–105.

———. Forthcoming. "Einstein's Special Theory of Relativity and the Problems in the Electrodynamics of Moving Bodies That Led Him to It." In *Cambridge Companion to Einstein*, edited by M. Janssen and C. Lehner. Cambridge: Cambridge University Press.

Sartori, Leo. 1996. *Understanding Relativity: A Simplified Approach to Einstein's Theories*. Berkeley and Los Angeles: University of California Press.

Schwartz, Joseph, and Michael McGuiness. 1979. *Einstein for Beginners*. New York: Pantheon.

Stachel, John et al., eds. 1987. *The Collected Papers of Albert Einstein. Volume 1: The Early Years: 1879–1902*. Princeton, NJ: Princeton University Press.

Wertheimer, Max. 1959. *Productive Thinking*. New York: Harper.

Whitrow, Gerald J., ed. 1973. *Einstein: The Man and His Achievements*. New York: Dover.

---

8 At the Limits of Possibility

Thought Experiments in Quantum Gravity

Mark Shumelda

1. INTRODUCTION: WHY QUANTIZE GRAVITY?

Each of the two pillars of twentieth-century physics—quantum mechanics and general relativity—has enjoyed both tremendous theoretical development as well as convincing empirical confirmation. Perhaps it is all the more surprising then that general relativity and quantum mechanics are completely incompatible with each other. The reasons for the incompatibility are many and include the ways in which space, time, matter, and energy are treated by the two theories (Callender and Huggett 2001a). Furthermore, attempts to quantize the gravitational field using the same renormalization group techniques that have produced quantum field theories for the other three fundamental forces (strong, weak, electromagnetic) have been a failure. "Quantum gravity" describes any attempt, of which there are many, to provide some solution to this problem.

But why should we expect the gravitational field to be quantized in the first place? After all, the energy and distance scales at which interactions between the quantum and gravitational fields are expected to become nonnegligible are truly extreme (e.g., the Planck length, 10^{-35}m). It turns out that an elegant thought experiment, proposed by Kenneth Eppley and Eric Hannah in 1977, lends strong credence to the view that the gravitational field must be quantized (Eppley and Hannah 1977). The thought experiment attempts to convince us that any theory combining a classical gravitational field with quantized matter is inconsistent. This result is particularly important since we currently lack particle accelerators powerful enough, or gravity wave detectors sensitive enough, to determine empirically whether or not gravity is quantized. In a word, quantum gravity is truly a "science without data."

Although Eppley and Hannah's thought experiment has enjoyed considerable success as an argument for the necessity of the quantization of the gravitational field, it is certainly not without its critics. The purpose of this paper is to defend the thought experiment and to propose a new, more nuanced role for it in the search for a quantum theory of gravity. I proceed as follows. Section 2 describes how the thought experiment works.

Routledge Studies in the Philosophy of Science

1. **Evolution, Rationality and Cognition**
   A Cognitive Science for the Twenty-First Century
   Edited by António Zilhão

2. **Conceptual Systems**
   Harold I. Brown

3. **Nancy Cartwright's Philosophy of Science**
   Edited by Stephan Hartmann, Carl Hoefer, and Luc Bovens

4. **Fictions in Science**
   Philosophical Essays on Modeling and Idealization
   Edited by Mauricio Suárez

5. **Karl Popper's Philosophy of Science**
   Rationality without Foundations
   Stefano Gattei

6. **Emergence in Science and Philosophy**
   Edited by Antonella Corradini and Timothy O'Connor

7. **Popper's Critical Rationalism**
   A Philosophical Investigation
   Darrell Rowbottom

8. **Conservative Reductionism**
   Michael Esfeld and Christian Sachse

9. **Models, Simulations, and Representations**
   Paul Humphreys and Cyrille Imbert

10. **Platonism, Naturalism, and Mathematical Knowledge**
    James Robert Brown

11. **Thought Experiments in Philosophy, Science, and the Arts**
    Edited by Mélanie Frappier, Letitia Meynell, and James Robert Brown

---

Thought Experiments in Philosophy, Science, and the Arts

Edited by Mélanie Frappier, Letitia Meynell, and James Robert Brown

Routledge
Taylor & Francis Group
NEW YORK LONDON