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How Hume and Mach Helped Einstein Find Special Relativity

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1. Introduction

In 1946, at the age of sixty-seven, Einstein sat down to record his autobiographical reminiscences of a life in science. Einstein's scientific work had then already become a revered source of stimulation for a new generation of philosophers who sought philosophical enlightenment in Einstein's physical theorizing. Einstein too had long made clear that there was a reverse influence: he in turn drew stimulation from the philosophical literature. From as early as 1912, one could read in his publications in physics that his work on general relativity had been motivated by the writings of Ernst Mach, especially through what Einstein had come to call "Mach's Principle." In his autobiographical reminiscences, Einstein now affirmed a similar debt for his special theory of relativity. Though this was not the first time he had made remarks of this type, their prominence in an otherwise brief and authoritative account of the discovery of special relativity could leave no doubt of their importance. He wrote of the decisive moment in which he abandoned the absoluteness of simultaneity and thereby discovered special relativity:

> Today everyone knows, of course, that all attempts to clarify this paradox [of light that leads to special relativity] satisfactorily were condemned to failure as long as the axiom of the absolute character of time, or of simultaneity, was rooted unrecognized in the unconscious. To recognize clearly this axiom and its arbitrary character already implies the essentials of the solution of the problem. The type of critical reasoning required for the discovery of this central point was decisively furthered, in my case, especially by the reading of David Hume's and Ernst Mach's philosophical writings. (Einstein 1949, 51)

An earlier remark in a letter of December 14, 1915, to Moritz Schlick makes the relative importance of Hume and Mach clear:

> Your exposition is also quite right that positivism suggested rel. theory, without requiring it. Also you have correctly seen that this line of thought was of great influence on my efforts and indeed E. Mach and still much more Hume, whose treatise on understanding I studied with eagerness and admiration shortly before finding relativity theory. (*Papers*, A, Vol. 8A, Doc. 165)

It was Hume more than Mach.

Einstein's avowal of intellectual debts to Hume and Mach have long been recognized and examined.[2] My purpose in this paper is to present a more detailed account of what, I believe, Einstein intended with these remarks, illuminating the account with recent work in the history of Einstein's discovery of special relativity.

I will suggest that what Einstein learned from Hume and Mach is not quite what one might initially expect. Einstein's discovery is concerned with space and, more essentially, time; and Hume and especially Mach's works are known for their critical analyses of the notions of space and time. Yet the match is not so perfect. Hume's and Mach's analyses of space and time address many aspects of the notions of space and time. But they pass over the specific aspect that was the entirety of Einstein's conceptual breakthrough of 1905: an analysis of the simultaneity of distant events that shows that observers in relative motion need not agree on which events are simultaneous. That is not to be found in Hume's and Mach's writings. What is to be found, however, is an account of the nature of concepts in general: concepts are dependent entirely on our sense impressions or sensations; they are inapplicable as representations of reality, that is, fictional, in so far as they extend beyond our sense experience.

Neither Hume nor Mach saw this fictional character as a tool that could be used in theory construction; fictional concepts were false representations to be eliminated from one's account of nature or at best tolerated if, as Hume held of causation, the elimination was unachievable. Here Einstein differed. One does not have to eliminate a fictional concept. Its presence indicated an arbitrariness in our physical theorizing. It could be retained as long as its arbitrary character was recognized and it was accommodated in such a way as to preclude unwitting introduction of false presumptions. At the decisive moment in his discovery of special relativity, Einstein did just this. He recognized that the traditional concept of the simultaneity of distant events was not fixed by experience; and that its use had tacitly committed us to a false presumption, the absoluteness of simultaneity — its independence from the state of motion of the observer. So he replaced it with a new concept of simultaneity. It was introduced by a freely chosen definition that exploited the arbitrariness of the concept. That definition brought no tacit commitment to the absoluteness of simultaneity. In the context of the postulates of his new theory, it led to the relativity of simultaneity, the dependence of judgments of simultaneity of distant events on the state of motion of the observer.

This paper will tell the story of Einstein's discovery and its debt to the writings of Hume and Mach. In Section 2, I will review the problems in electrodynamics that occupied Einstein for over seven years. Their recalcitrance finally led Einstein to seek a radical solution outside electrodynamics as a last desperate measure, a reformation of our notion of time and simultaneity. In Section 3, I will describe how Einstein justified this extraordinary departure by means of an austere account of the nature of concepts in scientific theories. In Section 4, I will seek to show how this account drew essentially on the writings of Mach and Hume. Section 4.3 contains some speculation over why Einstein singled out Hume over Mach. I will suggest that Mach's writings may have been less important since Einstein regarded them as denying the freedom of concept formation Einstein needed in 1905 to introduce his new definition of distant simultaneity. Finally in Section 5, by way of a conclusion, I will reflect on how Einstein's use of Hume's and Mach's philosophical writings was highly selective. His goals were as much to understand Hume's and Mach's thought as to find in them ideas that may be useful in his creative work as a physicist. Understandably this latter goal induced Einstein to be undeterred by systematic problems in Hume's and Mach's writings and to ignore consequences that did not suit his purpose of creating new physical theories.

To preclude confusion, let me stress here that I consider just the question of how Hume's and Mach's work figured in Einstein's discovery of special relativity in 1905. I shall not consider the large influence of Mach especially on Einstein's later work in general relativity.

2. Einstein's Electrodynamical Pathway to Special Relativity

Einstein (1952) recalled the long years of intense effort that preceded his 1905 discovery of special relativity—"the seven and more years that the development of the Special Theory of Relativity had been my entire life." Here I will review what we know of the struggles of these years, emphasizing that they were devoted almost entirely to grappling with problems in electrodynamics. That the real issue lay in a reconceptualization of the notion of simultaneity entered only in the final five to six weeks of his seven or more years of work. This review will help us to appreciate just what, on my best account, lay behind his reconceptualization of simultaneity and his drawing on the philosophical work of Hume and Mach. It was not an impulsive experiment in speculative philosophy. It was the culmination of years of labor, the adoption of a new approach to an old problem to which he was compelled by the failure of all other avenues. We might well suppose that the courage to take this step was supplied as much by his desperation to solve a stubbornly recalcitrant problem as by the persuasiveness of Hume's and Mach's writings.

While the review of this section gives a specific context for Einstein's reconceptualization of simultaneity in 1905, the account of later sections does not depend on the details of how Einstein came to identify simultaneity as the stumbling block. Perhaps all that really matters is that it came after years of failure with ordinary solutions, so that Einstein was willing to entertain something extraordinary.

2.1 *The magnet and conductor thought experiment*

Our documentation of Einstein's interest in the problems that led to special relativity begins with events as early as the summer of 1895, when a sixteen year old Einstein wrote an essay proposing experimental investigation of the electromagnetic ether, the medium proposed by 19th-century theories as the carrier of electromagnetic fields and light (*Papers*, Vol. 1, Doc. 5). This ether supplied a preferred state of rest for the universe, but a long tradition of experiments in the 19th century had failed to detect this state of rest. In the introductory section of the paper in which Einstein unveiled special relativity, "On the Electrodynamics of Moving Bodies," Einstein (1905) pointed to these experiments as grounds for doubting that there is an ether state of rest and as evidence for the principle of relativity, the assertion of the equivalence of all inertial states of motion. Traditional textbook accounts give pride of place to one of these experiments, the Michelson-Morley experiment. We now know that the experiment played only a minor role in Einstein's thoughts (see Holton 1969, Shankland 1963/73, and Stachel 1987). Einstein did know of the experiment prior to 1905 (as was finally revealed by Einstein's correspondence of 1899 — see *Papers*, Vol. 1, Doc. 57). However, it appeared to Einstein to do little more than support the idea that physics must conform to the principle of relativity; it did not establish the constancy of the speed of light, as later textbook accounts commonly assert.

These 19th-century experiments played some role in Einstein's thought. Einstein (1920) made clear, however, that another reflection provided the real impetus: "The phenomenon of magneto-electric induction

compelled me to postulate the (special) principle of relativity." Here Einstein referred to the magnet and conductor thought experiment that Einstein laid out in the opening sentences of his "On the Electrodynamics of Moving Bodies." While 19th-century experiments had revealed no ether state of rest, the theoretical structure of Maxwell's electrodynamics seemed to depend upon it. When a magnet is at rest in the ether, it is surrounded by a magnetic field. If the magnet is set in motion, however, the magnetic field changes in strength with time, as the magnet moves past some fixed point in the ether. That change, according to Maxwell's theory, causes a new entity to appear, an induced electric field as shown in Figure 1. (Einstein noted that the induced electric field has "a definite energy value," as if to emphasize its reality.)

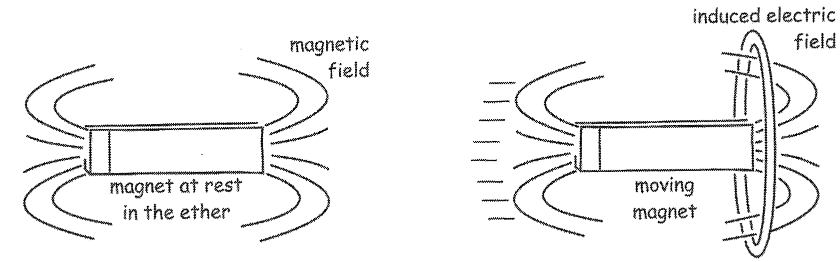

FIGURE 1. Magnets at rest and moving in the ether

One might suppose that this induced electric field would be an unequivocal indicator of whether the magnet is at rest in the ether or not, giving a direct observational means for distinguishing motion from rest in the ether. What Einstein realized was that this induced electric field could not be used as such an indicator because of an almost conspiratorial coincidence. To take a slightly simpler case than the one Einstein considered in 1905, imagine that an observer located on the magnet tries to test whether the induced electric field is present by looking for the current it engenders in a conductor:

- If the magnet is at rest in the ether, there would be no current simply because there is no induced electric field.
- If the magnet is moving in the ether, there would be an induced electric field and that field would generate a current in the conductor. However, a second effect, the motion of the conductor in the magnet's own magnetic field, would also induce a second current of exactly equal magnitude but opposite direction. The two currents would cancel and there would no net electric current in the conductor.

The electrodynamics of Einstein's time treated motion and rest of a magnet in the ether as very different cases. But as far as observables were concerned—the measurable current in a conductor—the two cases were the same. Once again experiment fails to reveal motion with respect to the ether state of rest. Einstein saw this as a strong indication that electrodynamics must somehow be modified so as to eradicate its dependence on this elusive state of rest; that is, it must be conformed to the principle of relativity.

The magnet and conductor thought experiment did a great deal more than just give Einstein the impetus to this conclusion. It also gave him a theoretical device that would later form an essential part of his completed theory. Classically, an electric field is an absolute quantity. Either it is present or not; and all observers, whatever their states of motion, would agree on its presence or absence. This is contrasted with relative quantities, such as the kinetic energy of a body. These quantities vary with the state of motion of the observer. A roadside observer will assign a large kinetic energy to a speeding car. The car occupants, however, will assign the car no kinetic energy, for the car is at rest with respect to them. Einstein's early deliberations on the magnet and conductor thought experiment revealed to him that an electric field had a similar relative existence. If one were at rest relative to the magnet, the field surrounding the magnet would manifest as a pure magnetic field. If one were in motion relative to the magnet, that same field would manifest as a magnetic field with an electric field. That is, the state of motion of the observer would determine whether or not the one field would appear to have an electric field within it or not.

The importance of this insight into field transformations was that it provided Einstein a theoretical device with which to implement the principle of relativity in electrodynamics, as has been pointed out by Earman et al. (1983) and Rynasiewicz (2000). The induced electric field of the magnet and conductor need no longer be regarded as revealing the absolute motion of the magnet. It now merely revealed the relative motion of magnet and observer—an effect fully in accord with the principle of relativity. All that was required was to find the general transformation law that would work in all cases and eliminate the need for an ether state of rest in the theory.

One might hope that this device could be used to implement the principle of relativity within Maxwell's electrodynamics and it is natural to suppose that Einstein explored the possibility. As I have shown in Norton (2004, Section 2),[3] the exploration would be encouraging, initially. Maxwell's electrodynamics is based on four field equations. Two only are needed to analyze the magnet and conductor thought experiment. As long as we consider them alone, it proves quite easy to find a field transformation law that allows an account of the magnet and conductor thought experiment, fully in accord with the principle of relativity. Further exploration rapidly generates disastrous consequences, however, and the most important is the following. The other two of Maxwell's equations can also be treated in a way that is in accord with the principle of relativity. However, one must use a *different* field transformation law for these other two equations. So Maxwell's theory cleaves into two parts, each of which can be made to conform to the principle of relativity, but not when they are joined. While Einstein would have had every reason to think that there was something very right in this notion of field transformations, he would also have had to see that something more was needed if electrodynamics was to be rendered compatible with the principle of relativity.

2.2 *An emission theory of light*

Using his device of field transformations, Einstein could bring conformity with the principle of relativity to one part of Maxwell's theory or to the other, but not to both together. It takes only a little reflection to see that this circumstance is inevitable. A theory that implements the principle of relativity in the context of ordinary Newtonian space and time must treat velocities in a quite particular way. Assume an observer watches a gun fire a bullet. The bullet velocity, as determined by the observer, must be given by the velocity of the bullet with respect to the gun added vectorially to the velocity of the gun with respect to the observer.

Now Maxwell's electrodynamics is also a theory of light; according to it, light consists merely of waves that propagate in the electromagnetic field. In the Newtonian context, the velocity of the propagation of light must be treated just as the velocity of everything else. By direct analogy with the bullet and gun, to determine the observed velocity of light we must add vectorially the velocity of propagation of light with respect to its emitter to the velocity of the emitter with respect to the observer. This rule is the characteristic property of a so-called "emission" theory of light. Any theory of light that implements the principle of relativity in the Newtonian context—that is, any "Galilean covariant" theory—must be an emission theory (but not conversely).

The difficulty Einstein faced is that Maxwell's electrodynamics cannot be an emission theory. One of the most important consequences of the theory is that light in a vacuum always propagates at the same speed, c=186,000 miles per second, with respect to the ether. Its velocity of propagation is unaffected by the velocity of the emitter. So Maxwell's theory cannot conform to the principle of relativity in a Newtonian context. This might not be apparent if we only look at each of the two parts of Maxwell's theory mentioned above individually. For neither part alone is sufficiently rich to determine a velocity of propagation for light. But the two parts combined are able to do this.

Einstein's response, as John Stachel (1982) emphasized, was to seek to modify Maxwell's theory in such a way as to convert it into an emission theory. Einstein left us no direct record of his explorations. The strongest clue of their contents lies in his repeated remarks that they were like those of Walter Ritz (1909a, 1909b), who, subsequently to the advent of special relativity, sought to construct a Galilean covariant, emission theory of electrodynamics and light. In Norton (2004, Sections 3–4; forthcoming, Section 4.3), I have put considerable effort into reconstructing the sort of theory that Einstein explored. It turns out that there is a single quite plausible theory that exploits Ritz's key theoretical maneuver while at the same time leaving unchanged that part of Maxwell's theory that treats the magnet and conductor, so that Einstein's device of field transformations could still be employed. While initially promising, this and all other Galilean covariant theories of electrodynamics prove unsatisfactory.

Combing through Einstein's later correspondence and writings we find a plethora of reasons given for the failure of an emission theory of light. The theory must fail, Einstein asserted, because the physical state of a light ray must be determined completely by its intensity, color and polarization; and an emission theory cannot be formulated as a field theory governed by differential equations; and an emission theory would allow light to back up on itself, in the sense that light emitted earlier by accelerating sources could be overtaken by light emitted later; and there would be problems with shadow formation. It is not at all straightforward to see how the objections work. I have urged (Norton 2004, Sections 5–6; Norton forthcoming, Section 4.3) that they can be put into cogent and compelling form if we embed them in Einstein's famous chasing a light beam thought experiments of his *Autobiographical Notes* (1949, 49–50). Indeed, I suggest, if we don't, it is hard to understand the importance Einstein accords to the thought experiment in his recollections.

For our purposes, what matters most is that these explorations, however they may have proceeded, required years of effort that brought[4] Einstein mounting frustration and a willingness to entertain a radical solution.

2.3 *"The Step"*[5]*: The relativity of simultaneity*

The breakthrough came some five to six weeks prior to completion of special relativity. Einstein faced an impasse in two incompatible demands. He felt compelled to conform Maxwell's electrodynamics (in the form given by Lorentz) to the principle of relativity, but that seemed impossible since Maxwell's electrodynamics required a constant speed for light. Yet all his

efforts to modify Maxwell's electrodynamics to an emission theory had failed. The tension could be reduced to the incompatibility of two requirements: the principle of relativity and the constancy of the speed of light.[6] Einstein suddenly realized these two requirements were not incompatible after all. The circumstances of this realization have become part of the heroic lore of discovery. Einstein recounted the story in a lecture in Kyoto on December 14, 1922:[7]

> Why are these two things inconsistent with each other? I felt that I was facing an extremely difficult problem. I suspected that Lorentz's ideas had to be modified somehow, but spent almost a year on fruitless thoughts. And I felt that was a puzzle not to be easily solved.
>
> But a friend of mine living in living in Bern (Switzerland) [Michele Besso] helped me by chance. One beautiful day, I visited him and said to him: 'I presently have a problem that I have been totally unable to solve. Today I have brought this "struggle" with me.' We then had extensive discussions, and suddenly I realized the solution. The very next day, I visited him again and immediately said to him: 'Thanks to you, I have completely solved my problem."
>
> My solution actually concerned the concept of time. Namely, time cannot be absolutely defined by itself, and there is an unbreakable connection between time and signal velocity. Using this idea, I could now resolve the great difficulty that I previously felt.
>
> After I had this inspiration, it took only five weeks to complete what is now known as the special theory of relativity.

What Einstein alluded to was his recognition, laid out in detail in Section 1 of his 1905 relativity paper, that the principle of relativity and the constancy of the speed of light could be rendered compatible if one was willing to allow that observers in relative motion might disagree on which spatially distant events are simultaneous. He argued that the simultaneity of spatially distant events could not be directly experienced. So we had to specify by a definition which spatially distant events were simultaneous.[8] Einstein's definition, in slightly modified form, is shown in Figure 2. An observer at the midpoint of a platform will judge the emission of light signals at clocks A and B at either end to be simultaneous, if those light signals arrive simultaneously at the observer.

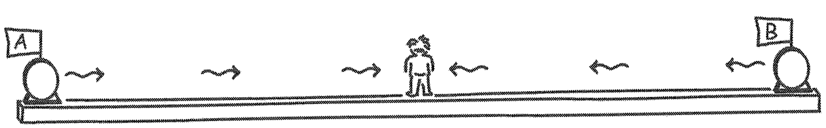

FIGURE 2. Einstein's definition of simultaneity

Innocuous as the definition may seem, Einstein proceeded to show that it yielded a startling conclusion if we also adhered to the principle of relativity and the constancy of the speed of light. Consider that same synchronization procedure, as it would appear to an observer who moves uniformly to the left. What that observer would see is shown in Figure 3.

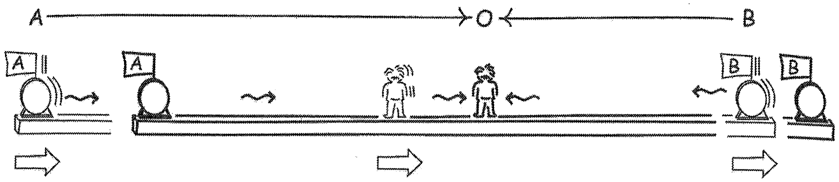

FIGURE 3. Einstein's procedure as seen by a moving observer

The new observer would judge the platform observer to be moving away from the signal emitted by clock A and towards the signal emitted by clock B. So, the fact that the signals arrive simultaneously at the platform observer shows that the two emission events were *not* simultaneous. The emission event at clock A must have happened earlier to give the light signal time to catch up with the fleeing platform observer; and the emission event at clock B must have happened later to compensate for the approach of the platform observer. In Figure 3, the signal from A must cover the greater distance AO and the signal from B must cover the lesser distance BO. Thus the platform and resting observer disagree on whether the two emission events are simultaneous, an illustration of the relativity of simultaneity.

This inference requires the constancy of the speed of light; the moving observer must also assign the same speed c to light in a vacuum. Thus a signal traversing the greater distance AO requires more time than one traversing the lesser BO. The deduction would fail if we assumed an emission theory since the moving observer would assign unequal speeds to the two signals. It also invokes the principle of relativity in so far as both observers use the same definition of simultaneity.

What Einstein's analysis shows is that the inconsistency of the principle of relativity and the constancy of the speed of light is only apparent. They can co-exist if we give up the notion that simultaneity is absolute, that is, the notion that all observers must agree on whether two events are simultaneous. That recognition also answers the obvious objection to attempts to retain both the principle of relativity and the constancy of the speed of light. If we conjoin them, we are to believe that all inertial observers will measure the same speed for light. But how can that be possible? If an observer chases after light at great speed, would not the moving observer measure a speed for light less than that of a resting observer? We can now see why that slowing need not happen. All judgments of the speed of light

depend upon measurements of time that use synchronized clocks. We might see how much time a light pulse takes to traverse a platform, such as shown in Figures 2 and 3, by comparing the times read by clocks A and B as the light pulse passes. If the two observers are in relative motion, they will disagree on the simultaneity of distant events. As a result, they will synchronize their clocks differently. If they both use Einstein's procedure of Figure 2 to synchronize their clocks, it is easy to see that each has adjusted the synchrony of their clocks in just the right way to ensure that each will measure the same constant c for the speed of light.[9]

Since judgments of simultaneity arise throughout kinematics, Einstein now needed to ascertain how our traditional notions of space and time must be modified to accommodate this new result of the relativity of simultaneity. That accommodation is the working out of the special theory of relativity, a new theory of space and time. The new theory solves Einstein's original problem of conforming Maxwell's electrodynamics to the principle of relativity. As Einstein showed in his 1905 paper, it turns out that, within the new theory of space and time, Maxwell's electrodynamics already conforms to the principle of relativity; all that was needed was the selection of the appropriate transformation rules for electric and magnetic fields. Indeed, as I show in a simple thought experiment in Norton (forthcoming, Section 4.2), the field transformation laws Einstein considered necessitate modifications to notions of simultaneity if they are used within Maxwell's theory.

3. Einstein's New View of Concepts

3.1 *Concepts must be grounded in experience*

What licensed Einstein's taking of "the step" is a new approach he explicitly decided to adopt towards concepts such as simultaneity in physical theory. The view is quite simple: a concept can properly represent something physically real only in so far as the concept is grounded in experience. That adopting this view enabled "the step" is expressed quite clearly in a 1924 recollection:[10]

> After seven years of reflection in vain (1898–1905), the solution came to me suddenly with the thought that our concepts and laws of space and time can only claim validity insofar as they stand in a clear relation to experiences; and that experience could very well lead to the alteration of the concepts and laws. By a revision of the concept of simultaneity into a more malleable form, I thus arrived at the special theory of relativity.

And Einstein elaborated the view in his 1916 interview with Max Wertheimer who reported:[11]

> . . . an illustration which Einstein offered in discussion. Suppose somebody uses the word 'hunchback.' If this concept is to have any clear meaning, there must be some way of finding out whether or not a man has a hunched back. If I could conceive of no possibility of reaching such a decision, the word would have no real meaning for me.
>
> 'Similarly,' Einstein continued, 'with the concept of simultaneity. The concept really exists for the physicist only when in a concrete case there is some possibility of deciding whether the concept is or is not applicable. Such a definition of simultaneity is required, therefore, as would provide a method for deciding. As long as this requirement is not fulfilled, I am deluding myself as physicist (to be sure, as non-physicist too!) if I believe that the assertion of simultaneity has real meaning.'

This view about the meaning of concepts can be found in Einstein's more general writings. His popular text on relativity theory (Einstein 1917, §8) asserts at the relevant moment: "The concept [of simultaneity] does not exist for the physicist until he has the possibility of discovering whether or not it is fulfilled in an actual case."

3.2 *The purging of the a priori from concepts*

Einstein's principal concern was the danger accompanying the use of concepts not properly grounded in experience. Use of a concept in a physical theory typically requires some sort of factual presumption. The danger was that use of a concept in a physical theory might inadvertently commit us to false physical presumptions, which we would introduce unwittingly as a kind of a priori knowledge, since it entered our theorizing merely through our choice of concepts and not through empirical investigation of the presumption. For example, before relativity theory, simultaneity was taken to be a two place relation between events. Events A and B could be simultaneous *simpliciter*; after relativity theory, it was recognized that events A and B can be simultaneous only with respect to an observer or frame of reference. So use of the older concept had required the tacit presumption that judgments of simultaneity are independent of observer or frame of reference.

Here is how Einstein recounted our failure to recognize the inadequate grounding in experience of distant simultaneity prior to relativity theory:

> The illusion which prevailed prior to the enunciation of the theory of relativity—that, from the point of view of experience the meaning of simultaneity in relation to spatially distant events and, consequently, that the meaning of physical time is a priori clear—this illusion had its origin in the fact that in our everyday experience we can neglect the time of propagation of light. We are accustomed on this account to fail to differentiate between "simultaneously seen" and "simultaneously happening"; and, as a result, the difference between time and local time is blurred.
>
> The lack of definiteness which, from the point of view of its empirical significance, adheres to the notion of time in classical mechanics was veiled by the axiomatic representation of space and time as given independently of our sense experiences. Such a use of notions—independent of the empirical basis to which they owe their existence—does not necessarily damage science. One may, however, easily be led into the error of believing that these notions, whose origin is forgotten, are logically necessary and therefore unalterable, and this error may constitute a serious danger to the progress of science. (Einstein 1936, 299)

Einstein urged that we preclude such unwitting introduction of a priori presumptions by proper attention to the experiences needed to warrant the application of the concept. Where no such experiences are possible, the concept is fictional or arbitrary. In his analysis in "On the Electrodynamics of Moving Bodies," Einstein had no difficulty identifying the experiences needed to warrant application of the concept of simultaneity for events at the same place. However, he could not identify experiences sufficient to warrant application of the concept of simultaneity for events at different places, so that concept is fictional or arbitrary. At this point, someone of a Machian bent would call for the purging of the concept from the theory as idle metaphysics with no grounding in experience. Einstein, however, was willing to retain the concept as long as its arbitrary character was recognized and in a way that no longer allowed the unwitting introduction of a priori presumptions. In the case of distant simultaneity, Einstein achieved this by introducing distant simultaneity through a definition—a freely chosen stipulation—carefully designed to minimize the danger of introducing false physical presumptions. In the context of Einstein's two postulates, his definition of simultaneity had the consequence that judgments of simultaneity of distant events would vary with changes of the state of motion of the observer. Einstein's procedure had purged kinematics of the false presumptions about simultaneity that permeated the Newtonian view of space and time.

4. The Debt to Mach and Hume

We have seen that Einstein expressed a debt to the philosophical writings of Hume and Mach in his discovery of special relativity. We are now in a position to see what that debt was. For the demand that concepts must be properly grounded in experience permeates both of their writings. Indeed much of their philosophical critiques amounts to the purging of a priori elements from concepts that do not meet this demand.

Because of the prominence of this view of concepts in Einstein's recollections of the breakthrough of 1905 and also in Hume and Mach's writings, I believe this view was the debt Einstein acknowledged to Hume and Mach, rather than any particular analysis by Hume and Mach of the notion of time. Of course, it is not so easy to disentangle the particular analyses of the notion of time from the general view of concepts. Mach's (1960, Ch. 2, §VII) celebrated critique of Newton's Absolute Space is simply a direct application of the general view. Newton's concept, Mach complains, is a fiction not given in the facts of experience. With only a little more effort, one finds Hume also applying his view of concepts to time in ways we could imagine impressing a young Einstein.[12] Since none of these analyses explicitly treat simultaneity, even if they were the ones that impressed him, Einstein would still need to abstract their general approach to concepts and then apply that abstracted approach to distant simultaneity in order to make the breakthrough of 1905.

4.1 *Mach*

While Einstein attributed greater influence to Hume, it is easier for us to see that Einstein found this view of concepts in Mach's writings. The reason is an appreciation Einstein wrote of Mach's work as Einstein's 1916 obituary for Mach. We need not read Mach's writings and try to ascertain how Einstein may have read or misread them and what in them attracted him. The obituary tells us directly how he read Mach's work and what he valued in it. What looms large in his appreciation is Mach's treatment of concepts just along the lines sketched above. Einstein (1916) described Mach's general orientation towards concepts, which contains the basic doctrine that concepts have meaning only in so far as they are empirically grounded:

> Science is, according to Mach, nothing but the comparison and orderly arrangement of factually given contents of consciousness, in accord with certain gradually acquired points of view and methods. . . .
> . . . concepts have meaning only in so far as they can be found in things, just as they are the points of view according to which these things are organized. (Analysis of concepts)

He proceeded then to find in Mach the warning against the use of concepts disconnected from their experiential grounding:

> Concepts that have proven useful in ordering things can easily gain authority over us such that we forget their worldly origin and take them as immutably given. They are then rather rubber-stamped as a 'necessity of thought' and an 'a priori given,' etc. Such errors often make the path of scientific progress impassable for a long time.

And then Einstein found in Mach the license to purge our theories of concepts that extend beyond their experiential grounding or to alter them to bring them into accord with that grounding:

> Therefore, it is not at all idle play if we are trained to analyze long familiar concepts, and to point out upon which circumstances their justification and usefulness depends; and how they evolved in particular from the givens of experience. Thereby their all too powerful authority is broken. They are removed, if they cannot properly be legitimized; they are corrected if their association with given things was too sloppy; they are replaced by others if a new system can be established that, for various reasons, we prefer.

These remarks refer to Mach's historico-critical approach to understanding our present scientific concepts through an account of their historical development, a central theme in Mach's critical writings on physics, whose importance Einstein recognized. Einstein then proceeded to illustrate how Mach applied this view in his well-known critiques of Newton's absolute space and time and mechanics (Mach 1960, Ch. 2. VII Newton's Views of Time, Space and Motion). The illustrations, quoted at length, are too well known to bear repetition here. Judgments of time are revealed to be really just expressions of dependence of one thing on another, such as the oscillations of a pendulum or the position of the earth; Newton's bucket experiment reveals only what happens when there is relative rotation between the water and the rest of the universe; it does not reveal an absolute motion, which has no grounding in sense experience.

Einstein here attributes to Mach the view of concepts that Einstein found decisive in his discovery of special relativity: concepts must be properly grounded in experience and there are great dangers in using concepts that fail to be so grounded. Einstein clearly made this same connection, for he proceeded to aver that Mach had just the critical apparatus needed to discover special relativity, if only he had worked in another time:

> It is not improbable that Mach would have hit upon relativity theory if, in the time that he was of young and fresh spirit, physicists would already have been moved by the question of the meaning of the constancy of the speed of light. In this absence of this stimulation, which follows from Maxwell-Lorentz electrodynamics, even Mach's critical urge did not suffice to arouse a feeling for the necessity of a definition of simultaneity for spatially distant events.

We must recall the context of Einstein's remarks, an obituary written to honor Mach. So we might well understand that Einstein here overlooked Mach's opposition to introducing arbitrary concepts into theories. Einstein was more forthright about the lack of fertility of Mach's approach the following May when he wrote to his friend Besso, "I do not inveigh against Mach's little horse; but you know what I think about it. It cannot give birth to anything living, it can only stamp out harmful vermin."[14] And again he averred in a lecture in Paris of 6 April 1922, ". . . in fact what Mach has done is to make a catalog, not a system."[15]

4.2 *Hume*

We saw above that Einstein informed Schlick in 1915 that Hume had "still much more" influence than Mach. However there is some uncertainty over just the work to which Einstein referred. He informed Schlick that he studied Hume's "treatise on understanding," "shortly before finding relativity theory." But does that betoken Hume's *A* Treatise *of Human Nature*? Or is it Hume's later *An Enquiry concerning Human* Understanding? I will follow the editors of *Papers*, Vol. 2, who decide the former is intended. They note (pp. xxiv–xxv) that the first part of Hume's *Treatise of Human Nature* was then available in a recently published German translation; that Einstein recalled reading Hume in German translation; and that it was known to belong to the reading list of the Olympia Academy, the small reading group formed by Einstein and his friends Conrad Habicht and Maurice Solovine in 1902.

If we turn to Hume's *Treatise*, we find that Hume's entire approach is based on a view of concepts that agrees with that of Einstein and Mach in the essential observation that concepts ("ideas") are grounded in sense experience ("impressions"). Hume concluded his introductory section (Book 1, Part 1, Section 1) with the synoptic assertion:

> . . . all our simple ideas proceed either mediately or immediately, from their correspondent impressions.
>
> This then is the first principle I establish in the science of human nature. . . .

Hume then unleashed this basic principle upon the ideas of metaphysics, demanding that they all derive from impressions. Hence, he noted, the idea of time depends upon our having changing impressions (Book 1, Part II, Section III):

> As 'tis from the disposition of visible and tangible objects we receive the idea of space, so from the succession of ideas and impressions we form the idea of time, nor is it possible for time alone ever to make its appearance, or be taken notice of by the mind.
>
> . . . time cannot make its appearance to the mind either alone, or attended with a steady unchangeable object, but is always discover'd by some *perceivable* succession of changeable objects.

What of ideas that extend beyond their grounding in impressions? These are denounced as falsehoods, as, for example, in the case of those who try to apply the notion of duration in time to perfectly unchangeable objects (Book 1, Part II, Section III):

> I know there are some who pretend, that the idea of duration is applicable in a proper sense to objects, which are perfectly unchangeable. . . . But to be convinced of its falsehood we need but reflect on the foregoing conclusion, that the idea of duration is always deriv'd from a succession of changeable objects, and can never be convey'd to the mind by any thing stedfast and unchangeable. For it inevitably follows from thence, that since the idea of duration cannot be deriv'd from such an object, it can never in any propriety or exactness be apply'd to it, nor can any thing unchangeable be ever said to have duration. Ideas always represent the objects or impressions from which they are deriv'd, and can never without a fiction represent or be appl'd to any other. . . .

This mode of analysis—illustrated here in its application to the notion of duration—is repeated throughout Hume's *Treatise*. What of the idea of substance, a substratum that carries properties? "We have therefore," Hume (Book 1, Part 1, Section VII) assures us, "no idea of substance, distinct from that of a collection of particular qualities, nor have we any other meaning when either talk or reason concerning it." Most famously this is the basis of Hume's celebrated critique of causation. There is no necessary connection relating cause to effect beyond the habit of mind that assigns it to the sorts of constant conjunction in sense experience that we call causal (Book 1, Part III, Sections XIV, XV).

4.3 *Why Hume more than Mach?*

Why was it that Hume influenced Einstein "still much more" than Mach in Einstein's discovery of relativity?[16] It might just have been happenstance. Perhaps Einstein read Hume at just the moment in his work on electrodynamics that reflections on the origin of our concepts were apposite. Or perhaps there is a relevant, systematic difference between Hume's and Mach's writings that might explain why Einstein found more inspiration in Hume.

There is such a difference. At the decisive moment, Einstein realized the fictional character of the concept of the simultaneity of distant events. He exercised the freedom implicit in this fictional character to assert through definition which distant events are simultaneous. The exercising of this freedom in turn calls to mind Einstein's frequent characterization of the concepts of scientific theories as "free creations of the human spirit." (For discussion, see Howard 2004, Section 2.) While Einstein seems to have found this freedom to conform with Hume's writings and perhaps even to be encouraged by them, he found it directly contradicted in Mach's writings.

Let us take Einstein's view of Mach first. As we saw in Section 4.1, Einstein may well have felt it inappropriate to dwell on Mach's philosophical weakness in writing Mach's obituary. However Einstein felt no such reservation years later in private correspondence with his old friend Besso. He wrote to Besso on 6. Jan. 1948:

> [Mach] took convincingly the position that these conceptions, even the most fundamental ones, obtained their warrant only out of empirical knowledge, that they are in no way *logically* necessary. . . . I see his weakness in this, that he more or less believed science to consist in a mere "ordering" of empirical "material"; that is to say, he did not recognize the freely constructive element in the formation of concepts. In a way he thought that theories arose through *discoveries* and not through *inventions*. He even went so far that he regarded "sensations" not only as material which has to be investigated, but, as it were, as the building blocks of the real world; thereby, he believed, he could overcome the difference between psychology and physics. If he had drawn the full consequences, he would have had to reject not only atomism but also the idea of a physical reality. (Speziali 1972, Doc. 153; translation Holton 1968, 231)

Mach's view of science as the mere ordering of sensations left Einstein no room for invention, the freedom of construction of concepts invoked in his 1905 definition of distant simultaneity.

Hume is mentioned in one other place in Einstein's *Autobiographical Notes*. Einstein noted (p.13):

> Hume saw clearly that certain concepts, as for example that of causality, cannot be deduced from the material of experience by logical methods.

A familiar aspect of Hume's view (e.g. Hume 1978, Book 1, Part III, Section IV, 165–66, 170) is that we proceed from sense impressions to the concept of cause by custom or habit. That aspect might well suggest to Einstein the sort of freedom in concept formation that Einstein invoked in his 1905 definition of simultaneity. At least Hume's view would seem compatible with this freedom, for Hume does not call upon us to eradicate the notion of causation as necessary connection, but merely to recognize its true origin and nature. However, Einstein read Mach's strict antimetaphysical attitude as directly contradicting this freedom.

4.4 *Taking the step*

We saw above that Einstein reported to Schlick that he had studied Hume's writing "shortly before finding relativity theory." So we can well imagine how the decisive moment came. After exploration upon exploration had led to nothing, Einstein finally saw that Maxwell's electrodynamics already conformed to the principle of relativity. That it appeared not to, he now saw, was an illusion fostered by the false presumption of absolute simultaneity. With the support of his readings of Hume and Mach, he determined that the concept of absolute simultaneity was fictional and he found the courage to discard it. In its place, he introduced a new definition of distant simultaneity, exercising the freedom to modify concepts that may have been encouraged by his reading of Hume, but not of Mach.

We have essentially no further clues as to the nature and even order of his deliberations at this moment. Since Einstein's later reporting of the relativity of simultaneity is routinely given in terms of clocks and how light signals may be used to synchronize them, it is easy to presume that Einstein discovered the relativity of simultaneity by reflection on clocks and light signals.[17] Elsewhere I have urged caution in making this presumption and explored other possibilities (Norton 2004, Sections 7–8; Norton forthcoming, Sections 4.5, 6). None of the deliberations Einstein reported prior to the step involve clocks and light signals. They pertain to light as a waveform extended in space, rather than as a signal, a spatially localized pulse.[18] There are other pathways Einstein could follow that did not require contemplation of clocks and synchronization by light signals. Lorentz's (1895) *Versuch*, which Einstein had read, used Lorentz's "theorem of corresponding states" to establish that optical experiments would not reveal the motion of the earth as long as it was slow.[19] Lorentz's result depended essentially on his use of "local time," which mathematically served precisely the same function as the relativity of simultaneity in special relativity. All that was needed was to give a different physical interpretation to Lorentz's mathematics. Might the step have been taken by Einstein, emboldened by Hume and Mach, recognizing that Lorentz's local time was just time and not a mathematical contrivance?

There is even an observational pathway to this conclusion. Einstein recalled two experiments as having been important in guiding him to special relativity: Fizeau's experiment on the speed of light in moving water and the observation of stellar aberration, the deflection of starlight due to the relative motion of the earth and the star. What is distinctive about the observed effects in both experiments is that they arise entirely from Lorentz's local time. That means that, in the context of special relativity, they arise entirely from differences in judgments of simultaneity by observers in relative motion. In the case of stellar aberration, for example, a wave front changes its direction of propagation as we transform between observers in different states of motion. The change of direction arises entirely because the two observers use different judgments of simultaneity in assembling the local fragments of the wave into a spatially extended wavefront at one instant. If Einstein noticed this, he would have found an observational basis for the relativity of simultaneity, largely independent of the details of Maxwell's electrodynamics and requiring no thought of clocks and their synchronization by light signals. My conjecture is that just such a recognition explains Einstein's attribution of importance to these two experiments.

5. Conclusion: Einstein as Physicist and Philosopher

When Einstein expressed a debt to the philosophical writings of Hume and Mach in his discovery of special relativity, he did not refer to a particular doctrine about space and time in their writings. While both cast their critical eyes on the notions of space and time, neither gave the sort of analysis of the concept of simultaneity that Einstein needed. Rather, what Einstein found helpful in their writings was a view about concepts. They must be grounded in experience and, in so far as they extended beyond that grounding, they are fictional or arbitrary. Rather than merely abjuring these fictional concepts (Mach) or at best tolerating them (Hume), Einstein saw them as revealing an arbitrariness in our physical theorizing.

The fictional concept could still be introduced through a freely chosen definition, as long as the definition did not tacitly commit us to false presumptions. That view of concepts enabled Einstein to abandon the notion of absolute simultaneity when he finally realized that this notion was all that obstructed his conforming of Maxwell's electrodynamics to the principle of relativity. He replaced it by a new notion of simultaneity introduced through a definition that did not commit him to the absoluteness of simultaneity.

In his "Reply to Critics" in the volume *Albert Einstein: Philosopher-Scientist* (1949a), Einstein mused that a scientist "must appear to the systematic epistemologist as a type of unscrupulous opportunist," drawing selectively on the views of the realist, idealist, positivist and Platonist as it suited the scientist's purposes. As Howard (2004) has noted, this selectivity may not betoken an incoherent position rather than one that agrees partially with each of the views listed. Nonetheless Einstein's selectivity is surely evident in the present episode in Einstein's use of the work of Hume and Mach. He takes those parts that serve his purpose in physical theory. But he ignores other less helpful consequences of their critiques and leaves the systematic elaboration of the philosophical doctrines to others. And we can hardly blame him since his goal is to develop new physical theories, not new philosophies.

To see the selectivity, consider a problem that Einstein did not address and which arises directly from the severity of Hume's critique. The application of his view of concepts led Hume, as we saw above, to the view that it is meaningless to apply the notion of duration in time to unchanging bodies. Einstein never seemed to adopt the full consequences of that conclusion; and if he had, it would have crippled his subsequent theorizing. It contradicts directly his famous cosmology of 1917, which models the universe as a uniform distribution of matter in space, both of which remain perfectly changeless over an infinity of time (Einstein 1917a). Indeed Einstein introduced this model exactly because he felt it met the demands of Mach's critique of inertia.

There is a deeper systematic difficulty. In formulating the view as requiring concepts to be 'grounded' in sense experience, I have chosen a somewhat vague locution. Just what does this grounding amount to? In the narrowest view, the meaning of the concept simply is the actual sense experience that grounds it. If that is the view, we must ask whether and how we can arrive at concepts that are *universally* meaningful when all our experiences are, it would seem, *specific*. Take two people who have sense experience of what we would ordinarily say are different instantiations of the same concept. In the narrowest view just mentioned, these two people would form different concepts on the basis of their sense experience. Yet if we reject this narrowest view, what sorts of extensions beyond the grounding experiences are admissible and why are they admissible?

This problem is tackled by Hume with some energy. He maintained that a concept can meaningfully extend beyond the specific impressions that ground it. While we cannot experience directly every one of the infinitely many shades of blue, Hume urged in the *Treatise* (Book 1, Part I, Section I) that we can readily conceive of a missing shade in a gradation of shades of blue presented to us, even though we may never have experienced this particular shade directly. It is not just that we can generalize from many instances of the same shade to the concept of that shade; we can also proceed to different shades.

Mach inclines towards a very lean reading of the grounding in experience. Science, he urged, was merely economical description of experience. He wrote (1882, 197, 207) that "Physics is experience, arranged in economical order," and "The goal which it [physical science] has set itself is the *simplest* and *most economical* abstract expression of facts." Thus he did deny the applicability of physical science beyond the actual facts at hand, this being the foundation of his critique of Newton's ideas of absolute space and time.

Mach's celebrated analysis of Newton's bucket experiment offers a clear statement of his resistance even to small extensions beyond actual fact, just as it shows that this austerity was too radical for Einstein. The relevant fact in the experiment is that, when a bucket of water rotates with respect to the remainder of the universe, there is a concavity formed in the surface of the water. Might this concavity be due to some sort of interaction between the water in the bucket and the distant stars? Would such an interaction mean that the walls of the bucket, if made leagues thick, would drag the water with it through this interaction when the walls were rotated? Mach recognized the temptation to guess at the possibility. However, in his celebrated remark on Newton's bucket, Mach denounced such theorizing. Or that, I believe, is the only reading that conforms to Mach's other pronouncements on science as an economical summary of experience. Mach wrote:

> Newton's experiment with the rotating vessel of water simply informs us, that the relative rotation of the water with respect to the sides of the vessel produces no noticeable centrifugal forces, but that such forces *are* produced by its relative rotation with respect to the mass of the earth and the other celestial bodies. No one is competent to say how the experiment would turn out if the sides of the vessel increased in thickness and mass till they were ultimately several leagues thick. The one experiment lies before us, and our business is, to bring it into accord with the other facts known to us, and not with the arbitrary fictions of our imagination. (Mach 1960, 284)

As I have discussed in detail elsewhere (Norton 1993), Einstein's response to this same problem is revealing. He chose to endorse exactly the speculation that Mach disavowed. Einstein inferred that the walls of a very massive bucket, if rotating, would drag the water, attributing this same conclusion to Mach. That conclusion became his "relativity of inertia" and later "Mach's principle," the notion that drove Einstein through years of theorizing on general relativity, before he abandoned it.

Einstein chose fertility for a new physical theory over philosophical cogency. So how did Einstein explain that concepts can supply us meaningful content beyond the experiences that ground them? He wrote:

> The very fact that the totality of our sense experiences is such that by means of thinking (operations with concepts, and the creation and use of definite functional relations between them, and the coordination of sense experiences to these concepts) it can be put in order, this fact is one which leaves us in awe, but which we shall never understand. One may say "the eternal mystery of the world is its comprehensibility." . . . In speaking here of "comprehensibility," the expression is used in its most modest sense. It implies: the production of some sort of order among sense impressions, this order being produced by the creation of general concepts, relations between these concepts, and by definite relations of some kind between the concepts and sense experience. It is in this sense that the world of our sense experiences is comprehensible. The fact that it is comprehensible is a miracle. (Einstein 1936, 292)

His explanation—that it is a wondrous miracle beyond our comprehension—would surely be the last resort of a desperate philosopher. But it is a comfortable resting point for a physicist whose real concern lies in physical theory and who wants to call up philosophical analysis only when it suits his physical ends.[20]

NOTES

1. It is a pleasure to present this paper in honor of my colleague and friend, Michael Friedman, whose work on the entanglements of science and philosophy has enlightened and energized us all. I thank Dan Steel for pointing out to me years ago the connection between Einstein's work of 1905 and Hume's critique of concepts and causality. I am grateful for helpful discussion to Stephen Engstrom, Don Howard, Gerald Massey, Paul Pojman and the participants in the conference "Synthesis and the Growth of Knowledge" (University of South Carolina, October 1–3, 2004); to its tireless organizers, Michael Dickson and Mary Domski; and especially to Robert Rynasiewicz for his unflinching resolve in bringing criticisms

of an earlier version of this paper to my notice, some of which proved to be correct and important.

2. This literature is enormous. For an entry into it, see Holton (1968), Stachel, et al. (1989a), and, most recently, Howard (2004).

3. For a simplified account, see Norton (forthcoming, Section 4).

4. As a footnote to Einstein's (1920) recollection of the magnet and conductor thought experiment he wrote, "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." Wertheimer (1959, 216) also reports on the strength of interviews with Einstein in 1916 that Einstein was occupied with the problem "for years."

5. As Pais (1982, 163) reports Einstein called the breakthrough.

6. Knowing what is about to ensue, it is hard for modern readers to do anything but applaud Einstein's stubborn insistence that we eliminate the ether state of rest from physics in favor of the principle of relativity. But the situation was not so straightforward in 1905. Physicists had learned to accommodate principles whose truth was contradicted by the basic entities of the science. For example, the second law of thermodynamics, Carnot's principle, assured us of an inexorable rise in entropy with time. The atomic theory of matter, however, asserted that this rise was only very probable, with that assertion resting on the existence of atoms that were by supposition so small as to elude direct detection.

7. The story quoted is from notes taken by Jun Ishiwara. Multiple translations of uncertain quality can be found. The one given is from Stachel (2002, 185).

8. In this sense, Einstein deemed judgments of the simultaneity of distant events to be conventional. To what extent did his views conform to the thesis of the "conventionality of simultaneity," as developed by Reichenbach and many others? (See Janis 2002.) One might think that Einstein would have to subscribe to this thesis were he only to pursue the logical consequences of his assertion that distant simultaneity can be introduced by a definition. He would then be committed to many of the familiar consequences of the thesis, such as the admissibility of non-standard ε-coordinate systems and the division of all physical quantities into factual two-way quantities and conventional one-way quantities. Yet outside of the first part of his 1905 paper, Einstein makes no systematic acknowledgement of this distinction of one-way and two-way quantities; and his treatment of coordinate systems is sufficiently different from our modern approach as to make it unlikely that he would have regarded a non-standard ε-coordinate system as licit in special relativity. (See Norton 1989 and 1992.)

9. Does this mean that the constancy of the speed of light is a conventional artifact of how we set our clocks? It does not. Einstein's definition of simultaneity requires certain facts to obtain. It would fail if an emission theory of light were true, since such a theory allows light to have many speeds. And it would fail in an ether theory, with light propagating at c with respect to the ether. For observers moving at c would find light frozen and be unable to use it to determine the simultaneity of events.

10. This is a translation in *Papers* Vol. 2, p. 264, of a voice recording, transcribed and presented in the German in Herneck (1966).

11. While Wertheimer presents the remarks as a quotation, they are more likely recreations from notes.

12. Having asserted that we have no means to ascertain exact equality of measure for geometrical figures, Hume urged that the idea of a perfect correction of imperfect, real measures "is a mere fiction of the mind, and useless as well as incomprehensible" (Hume 1978, Book 1, Part II, Section IV). He then extended the critique to the notion of the duration of time:

> This appears very conspicuously with regard to time; where tho' 'tis evident we have no exact method of determining the proportions of parts, not even so exact as in extension, yet the various corrections of our measures, and their different degrees of exactness, have given us an obscure and implicit notion of a perfect and entire equality.

I am grateful to Gerald Massey for drawing my attention to this discussion.

13. The translations that follow are based loosely on Engel (1997).

14. 13 May 1917; *Papers*, Vol. 8a, Doc. 339. Translation from Holton (1968, 240).

15. As quoted in Holton (1968, 239).

16. The remark is repeated in a somewhat vaguer context in a letter by Einstein to his old friend Besso of 6 Jan. 1948 (Speziali, 1972, Doc. 153). Responding to a suggestion by Besso of Mach's influence, Einstein responded:

> Now, as far as Mach's influence on my development is concerned, it was certainly great. . . . How far [Mach's writings] influenced my own work is, to be honest, not clear to me. In so far as I can be aware, the immediate influence of D. Hume on me was greater. I read him with Konrad Habicht and Solovine in Bern. However, as I said, I am not in a position to analyze what is anchored in unconscious thought.

17. In this regard, we may well wonder if Einstein was informed by Poincaré's earlier analysis of Lorentz's local time in terms of light signals and clocks. More generally, we may wonder whether Einstein drew on Poincaré's conventionalist views when Einstein invoked the freedom to fix the concept of simultaneity through chosen definitions. If Einstein hit upon the relativity of simultaneity without reflecting on clocks and light signals, a possibility we cannot rule out, then there would be no significant role for Poincaré's analysis of local time. Moreover, if a reading of Poincaré's work was important to Einstein's taking of the step, we should ask why he acknowledges help only from Hume and Mach in stating the philosophical debts incurred in the discovery of special relativity. Einstein did elsewhere acknowledge a debt to Poincaré. For example, writing to Besso on 6 March 1952 (Speziali 1972, Doc. 182) of his early readings with Habicht and Solovine, he noted: "These readings [of Hume] were of considerable influence on my development—along with Poincaré and Mach." But nothing in this acknowledgement specifically suggests the discovery of special relativity. Poincaré's name is not mentioned elsewhere in *Autobiographical Notes.* Poincaré does figure prominently in the appended "Reply to Criticisms" (1949a). But Poincaré is discussed only for his contribution to the discussion of the conventionality of geometry. For further discussion, see Darrigol 1996, 302; Darrigol 2004.

18. Einstein recalled in several places that the insight came to him suddenly, suggesting that he may not have needed to develop a new framework of clocks and synchronization procedures to see it. See Einstein's 1922 recollections in Kyoto above ". . . and suddenly I realized the solution . . ." and in the 1924 recording ". . . the solution came to me suddenly with the thought that our concepts . . . ."

19. More precisely, there would be no observable effect in quantities of the first order in v/c, where v is the speed of the earth.

20. This is not to say that Einstein's selectivity was inadvertent. Indeed, as we saw in Einstein's remarks to Besso of 6 Jan 1948 (Section 4.3 above), Einstein was fully aware of the austerity of Mach's system and properly complained that a full development of Mach's views would bring not just skepticism about atoms but about physical reality itself.

REFERENCES

Asquith, P.D. and T. Nickles (eds.) (1983). *PSA 1982.* East Lansing: Philosophy of Science Association.

Barbour, J. and H. Pfister (eds.) (1993). *Mach's Principle: From Newton's Bucket to Quantum Gravity.* Einstein Studies. Boston: Birkhäuser.

Darrigol, O. (1996). "The Electrodynamic Origins of Relativity Theory." *Historical Studies in the Physical Sciences* 26: 241–312.

———. (2004). "The Mystery of the Einstein-Poincaré Connection." *Isis* 95: 614–26.

Earman, J., C. Glymour, and R. Rynasiewicz (1983). "On Writing the History of Special Relativity." In Asquith and Nickles (eds.), Volume 2, 403–16.

Einstein, A. (1905). "Zur Electrodynamik bewegter Körper." *Annalen der Physik* 17: 891–921. Translated as "On the Electrodynamics of Moving Bodies," in Lorentz et al. (1952), 37–65.

———. (1916). "Ernst Mach." *Physikalische Zeitschrift* 17: 101–104; *Papers*, Vol. 6, Doc. 29.

———. (1917). *Über die spezielle and die allgemeine Relativitätstheorie (Gemeinverständlich).* Braunschweig: Friedr. Vieweg & Sohn; *Papers*, Vol. 6, Doc. 42. 15th expanded edition. Translated by R.W. Lawson (1954), *Relativity: the Special and the General Theory.* London: Methuen.

———. (1917a). "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie." In *Preussische Akademie der Wissenschaften, Sitzungs-berichte*, 142–52; translated as "Cosmological Considerations on the General Theory of Relativity," in Lorentz et al. (1952), 175–88.

———. (1920). "Fundamental Ideas and Methods of the theory of Relativity, Presented in Their Development." *Papers*, Vol. 7, Doc. 31.

———. (1936). "Physics and Reality." In *Ideas and Opinions*, 290–323. New York: Bonanza, n.d.

———. (1949). Autobiographical Notes. P.A. Schilpp (ed.) La Salle and Chicago: Open Court. Reprinted and corrected from P.A. Schilpp (1944).

———. (1949a). "Remarks Concerning the Essays Brought Together in this Co-operative Volume" (Running Heading: "Reply to Criticisms"). In P.A. Schilpp (ed.) (1949), 1–94.

———. (1952). "In Memory of Albert A. Michelson on his 100th Birthday." Einstein Archive 1–168.00; facsimile, Einstein Archives Online, URL = http://www.alberteinstein.info

Eisenstaedt, J. and A. Kox (eds.) (1992). *Studies in the History of General Relativity: Einstein Studies.* Vol. III Boston: Birkhäuser.

Engel, A. (1997). *The Collected Papers of Albert Einstein. Volume 6. The Berlin Years: Writings, 1914–1917. English Translation of Selected Texts.* E. Schucking, consultant. Princeton: Princeton University Press.

Herneck, F. (1966). "Zwei Tondokumente Einsteins zur Relativitätstheorie." *Forschungen und Fortschritte* 40: 133–35.

Holton, G.J. (1968). "Einstein, Mach, and the Search for Reality." In G.J. Holton (1973), 219–59.

———. (1969). "Einstein, Michelson and the 'Crucial' Experiment." *Isis* 60: 133–69; Ch. 9 in G.J. Holton (1973).

———. (1973). *Thematic Origins of Scientific Thought: Kepler to Einstein.* Cambridge, MA: Harvard University Press.

Howard, D.A. and J. Stachel (eds.) (2000). *Einstein, The Formative Years, 1879–1909: Einstein Studies, Volume 8.* Boston: Birkhäuser.

Howard, D.A. (2004). "Einstein's Philosophy of Science." *The Stanford Encyclopedia of Philosophy* (Spring 2004 Edition), Edward N. Zalta (ed.), URL = plato.stanford.edu/archives/spr2004/entries/einstein-philscience.

Hume, D. (1978). *A Treatise of Human Nature.* 2nd ed. Oxford: Clarendon.

———. (1988). *An Enquiry concerning Human Understanding.* Chicago, IL: Open Court.

Janis, A. (2002). "Conventionality of Simultaneity", *The Stanford Encyclopedia of Philosophy* (Fall 2002 Edition), Edward N. Zalta (ed.), URL = plato.stanford.edu/archives/fall2002/entries/space-time-convensimul.

Janssen, M. et al. (2002). *The Collected Papers of Albert Einstein: Volume 7: The Berlin Years: Writings, 1918–1921.* Princeton: Princeton University Press. ("*Papers*, Vol. 7.")

Janssen, M. and C. Lehner (eds.) (forthcoming). *Cambridge Companion to Einstein.* Cambridge: Cambridge University Press.

Kox, A.J., et al. (eds.) (1996). *The Collected Papers of Albert Einstein: Volume 6: The Berlin Years: Writings, 1914–1917.* Princeton: Princeton University Press. ("*Papers*, Vol. 6.")

Lorentz, H.A. (1895). *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern.* Leiden: E.J. Brill.

Lorentz, H.A., et al. (1952). *The Principle of Relativity: A Collection of Original Memoirs on the Special and General Theory of Relativity.* With notes by A. Sommerfeld ; translated by W. Perrett and G.B. Jeffery. New York: Dover.

Mach, E. (1882). "The Economical Nature of Physical Inquiry." In Mach (1943), 186–213.

———. (1943). *Popular Scientific Lectures.* 5th ed.. Translated by T.J. McCormach. LaSalle, Illinois: Open Court.

———. (1960). *The Science of Mechanics: A Critical and Historical Account of Its Development.* 6th ed. Translated by T.J. McCormach from the ninth German edition. La Salle, IL: Open Court.

Norton, J.D. (1989). "Coordinates and Covariance: Einstein's View of Spacetime and the Modern View." *Foundations of Physics* 19: 1215–63.

———. (1992). "The Physical Content of General Covariance." In Eisenstaedt and Kox (eds.) (1992), 281–315.

———. (1993). "Mach's Principle before Einstein." In Barbour and Pfister (eds.) (1993) Vol. 6., 9–57.

———. (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 Janssen and Lehner (eds.).

Pais, A. (1982). *Subtle is the Lord: The Science and the Life of Albert Einstein.* Oxford: Clarendon.

Ritz, W. (1909a). "Über die Grundlagen der Elektrodynamik und die Theorie der Schwarzen Strahlung." *Physikalische Zeitschrift* 9: 903–907; reprinted as Ritz (1911), 493–502.

———. (1909b). "Zum gegenwärtigen Stand des Strahlungsproblems: Erwiderung auf den Aufsatz des Herrn A. Einstein." *Physikalische Zeitschrift* 10: 224–25.

———. (1911). *Gesammelte Werke. Oeuvres.* Paris: Gauthier-Villars.

Rynasiewicz, R. (2000). "The Construction of the Special Theory: Some Queries and Considerations." In Howard and Stachel (eds.), 159–201.

Shankland, R.S. (1963/73). "Conversations with Einstein." *American Journal of Physics* 31(1963): 47–57; 41(1973): 895–901.

Schilpp, P.A. (ed.) (1949). *Albert Einstein: Philosopher-Scientist.* Evanston, IL: Library of Living Philosophers.

Schulmann, R., A.J. Kox, M. Janssen, and J. Illy (eds.) (1998). *The Collected Papers of Albert Einstein. Volume 8. The Berlin Years: Correspondence, 1914–1918. Part A: 1914–1917.* Princeton: Princeton Univ. Press. ("*Papers*, Vol. 8A").

Speziali, P. (ed.) (1972). *Albert Einstein Michele Besso: Correspondence.* Paris: Hermann.

Stachel, J. (1982). "Einstein and Michelson: the Context of Discovery and Context of Justification." *Astronomische Nachrichten* 303: 47–53; reprinted in Stachel (2002), 177–90.

———. (1987). "Einstein and Ether Drift Experiments." *Physics Today* 40: 45–47; reprinted in Stachel (2002), 171–76.

———. (2002). *Einstein from 'B' to 'Z.': Einstein Studies, Volume 9.* Boston: Birkhäuser.

Stachel, J., et al. (eds.) (1987). *The Collected Papers of Albert Einstein: Volume 1: The Early Years: 1879–1902.* Princeton: Princeton University Press. ("*Papers*, Vol. 1")

———. (eds.) (1989). *The Collected Papers of Albert Einstein: Volume 2: The Swiss Years: Writing, 1900–1902.* Princeton: Princeton University Press. ("*Papers*, Vol. 2.").

———. (1989a). "Einstein on the Theory of Relativity." Headnote in *Papers*, Vol. 2, 253–74.

Wertheimer, M. (1959). *Productive Thinking.* New York: Harper & Bros.

[17]

The Paracletes of Quantum Gravity

JAMES MATTINGLY [1]

1. Background for Quantum Gravity

The physics community is embroiled in a profound and far-reaching revolution, a revolution that will overturn the bedrock theories of matter, space-time, and gravity on which almost all of the physical theories of the twentieth century depend. This revolution is pressing and urgent and now is the time to choose up sides. At stake is no less than the theory of quantum gravity!

However, since the revolution is now in at least its fifty-fifth year, it may be time to take stock and make some suggestions about what might be slowing it down, and about what strategic moves might advance the cause.

In the twentieth century physicists developed two of the most successful descriptions of nature ever produced, general relativity and quantum mechanics. General relativity, Einstein's theory of gravitation, rejects the notion of gravitational force and replaces it with a conception of gravitational interaction carried out by changes in the actual geometry of space and time, now space-time; these changes in geometry reflect the distorting effect of matter and energy in space-time. The story is complicated in its details, but simple in its conception: the presence of matter distorts the geometry of space-time where the matter is located, and these changes are propagated at the speed of light throughout space-time; on the other hand, matter not subject to outside forces travels on geodesics, the straightest paths in space-time. This mutual interaction between space-time and the matter-energy fields therein gives rise to behavior that, in the limit of small masses (planets, moons), reproduces the appearances of Newton's theory of gravity but that deviates from the predictions of that theory in the case of larger masses (suns, galaxies). As is well known, the

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