



Mach, Einstein, and the Search for Reality

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ANTICIPATIONS

GERALD HOLTON

Mach, Einstein, and the Search for Reality

IN THE history of ideas of our century, there is a chapter that might be entitled "The Philosophical Pilgrimage of Albert Einstein," a pilgrimage from a philosophy of science in which sensationism and empiricism were at the center, to one in which the basis was a rational realism. This essay, a portion of a more extensive study,¹ is concerned with Einstein's gradual philosophical reorientation, particularly as it has become discernible during the work on his largely unpublished scientific correspondence.²

The earliest known letter by Einstein takes us right into the middle of the case. It is dated 19 March 1901 and addressed to Wilhelm Ostwald.³ The immediate cause for Einstein's letter was his failure to receive an assistantship at the school where he had recently finished his formal studies, the Polytechnic Institute in Zürich; he now turned to Ostwald to ask for a position at his laboratory, partly in the hope of receiving "the opportunity for further education." Einstein included a copy of his first publication, "Folgerungen aus den Capillaritätserscheinungen" (*Annalen d. Physik*, Vol. 4 [1901], p. 513), which he said had been inspired (*angeregt*) by Ostwald's work; indeed, Ostwald's *Allgemeine Chemie* is the first book mentioned in all of Einstein's published work.

Not having received an answer, Einstein wrote again to Ostwald on 3 April 1901. On 13 April 1901 his father, Hermann Einstein, sent Ostwald a moving appeal, evidently without his son's knowledge. Hermann Einstein reported that his son esteems

Mach, Einstein, and the Search for Reality

Ostwald “most highly among all scholars currently active in physics.”⁴

The choice of Ostwald was significant. He was, of course, not only one of the foremost chemists, but also an active “philosopher-scientist” during the 1890’s and 1900’s, a time of turmoil in the physical sciences as well as in the philosophy of science. The opponents of kinetic, mechanical, or materialistic views of natural phenomena were vociferous. They objected to atomic theory and gained great strength from the victories of thermodynamics, a field in which no knowledge or assumption was needed concerning the detailed nature of material substances (for example, for an understanding of heat engines).

Ostwald was a major critic of the mechanical interpretation of physical phenomena, as were Helm, Stallo, and Mach. Their form of positivism—as against the sophisticated logical positivism developed later in Carnap and Ayer’s work—provided an epistemology for the new phenomenologically based science of correlated observations, linking energetics and sensationism. In the second (1893) edition of his influential textbook on chemistry, Ostwald had given up the mechanical treatment of his first edition for Helm’s “energetic” one. “Hypothetical” quantities such as atomic entities were to be omitted; instead, these authors claimed they were satisfied, as Merz wrote around 1904, with “measuring such quantities as are presented directly in observation, such as energy, mass, pressure, volume, temperature, heat, electrical potential, etc., without reducing them to imaginary mechanisms or kinetic quantities.” They condemned such conceptions as the ether, with properties not accessible to direct observation, and they issued a call “to consider anew the ultimate principles of all physical reasoning, notably the scope and validity of the Newtonian laws of motion and of the conceptions of force and action, of absolute and relative motion.”⁵

All these iconoclastic demands—except anti-atomism—must have been congenial to the young Einstein who, according to his colleague Joseph Sauter, was fond of calling himself “a heretic.”⁶ Thus, we may well suspect that Einstein felt sympathetic to Ostwald who denied in the *Allgemeine Chemie*⁷ that “the assumption of that medium, the ether, is unavoidable. To me it does not seem to be so. . . . There is no need to inquire for a carrier of it when we find it anywhere. This enables us to look upon radiant energy as independently existing in space.” It is a position quite consistent

with that shown later in Einstein's papers of 1905 on photon theory and relativity theory.

In addition, it is worth noting that Einstein, in applying to Ostwald's laboratory, seemed to conceive of himself as an experimentalist. We know from many sources that in his student years in Zürich Einstein's earlier childhood interest in mathematics had slackened considerably. In the *Autobiographical Notes*,⁸ Einstein reported: "I really could have gotten a sound mathematical education. However, I worked most of the time in the physical laboratory, fascinated by the direct contact with experience" (p. 15). To this, one of his few reliable biographers adds: "No one could stir him to visit the mathematical seminars. . . . He did not yet see the possibility of seizing that formative power resident in mathematics, which later became the guide of his work. . . . He wanted to proceed quite empirically, to suit his scientific feeling of the time. . . . As a natural scientist, he was a pure empiricist." (Anton Reiser, *Albert Einstein* [New York, 1930], pp. 51-52.)

Ostwald's main philosophical ally was the prolific and versatile Austrian physicist and philosopher Ernst Mach (1838-1916), whose main work Einstein had read avidly in his student years and with whom he was destined to have later the encounters that form a main concern of this paper. Mach's major book, *The Science of Mechanics*,⁹ first published in 1883, is perhaps most widely known for its discussion of Newton's *Principia*, in particular for its devastating critique of what Mach called the "conceptual monstrosity of absolute space" (Preface, 7th Edition, 1912)—a conceptual monstrosity because it is "purely a thought-thing which cannot be pointed to in experience." Starting from his analysis of Newtonian presuppositions, Mach proceeded in his announced program of eliminating all metaphysical ideas from science. As Mach said quite bluntly in the preface to the first edition of *The Science of Mechanics*: "This work is not a text to drill theorems of mechanics. Rather, its intention is an enlightening one—or to put it still more plainly, an anti-metaphysical one."

It will be useful to review briefly the essential points of Mach's philosophy. Here we can benefit from a good, although virtually unknown, summary presented by his sympathetic follower, Moritz Schlick, in the essay "Ernst Mach, Der Philosoph."¹⁰

Mach was a physicist, physiologist, and also psychologist, and his philosophy . . . arose from the wish to find a principal point of view to which he could hew in any research, one which he would not have to change

Mach, Einstein, and the Search for Reality

when going from the field of physics to that of physiology or psychology. Such a firm point of view he reached by going back to that which is given before all scientific research: namely, the world of sensations. . . . Since all our testimony concerning the so-called external world rely only on sensations, Mach held that we can and must take these sensations and complexes of sensations to be the sole contents [*Gegenstände*] of those testimonies, and, therefore, that there is no need to assume in addition an unknown reality hidden behind the sensations. With that, the existence *der Dinge an sich* is removed as an unjustified and unnecessary assumption. A body, a physical object, is nothing else than a complex, a more or less firm [we would say, invariant] pattern of sensations, i.e., of colors, sounds, sensations of heat and pressure, etc.

There exists in this world nothing whatever other than sensations and their connections. In place of the word "sensations," Mach liked to use rather the more neutral word "elements." . . . [As is particularly clear in Mach's book *Erkenntnis und Irrtum*,] scientific knowledge of the world consists, according to Mach, in nothing else than the simplest possible description of the connections between the elements, and it has as its only aim the intellectual mastery of those facts by means of the least possible effort of thought. This aim is reached by means of a more and more complete "accommodation of the thoughts to one another." This is the formulation by Mach of his famous "principle of the economy of thought."¹¹

The influence of Mach's point of view, particularly in the German-speaking countries, was enormous—on physics, on physiology, on psychology, and on the fields of the history and the philosophy of science¹² (not to mention Mach's profound effect on the young Lenin, Hofmannstal, Musils, among many others outside the sciences). Strangely neglected by recent scholarship—there is not even a major biography—Mach has in the last two or three years again become the subject of a number of promising studies. To be sure, Mach himself always liked to insist that he was beleaguered and neglected, and that he did not have, or wish to have, a philosophical system; yet his philosophical ideas and attitudes had become so widely a part of the intellectual equipment of the period from the 1880's on that Einstein was quite right in saying later that "even those who think of themselves as Mach's opponents hardly know how much of Mach's views they have, as it were, imbibed with their mother's milk."¹³

The problems of physics themselves at that time helped to reinforce the appeal of the new philosophical attitude urged by Mach. The great program of nineteenth-century physics, the reconciliation of the notions of ether, matter, and electricity by means of mechanistic pictures and hypotheses, had led to enormities—for

example, Larmor's proposal that the electron is a permanent but movable state of twist or strain in the ether, forming discontinuous particles of electricity and possibly of all ponderable matter. To many of the younger physicists of the time, attacking the problems of physics with conceptions inherited from classical nineteenth-century physics did not seem to lead anywhere. And here Mach's iconoclasm and incisive critical courage, if not the details of his philosophy, made a strong impression on his readers.

Mach's Early Influence on Einstein

As the correspondence at the Einstein Archives at Princeton reveals, one of the young scientists deeply caught up in Mach's point of view was Michelange (Michele) Besso—Einstein's oldest and closest friend, fellow student, and colleague at the Patent Office in Bern, the only person to whom Einstein gave public credit for help (*manche wertvolle Anregung*) when he published his basic paper on relativity in 1905. It was Besso who introduced Einstein to Mach's work. In a letter of 8 April 1952 to Carl Seelig, Einstein wrote: "My attention was drawn to Ernst Mach's *Science of Mechanics* by my friend Besso while a student, around the year 1897. The book exerted a deep and persisting impression upon me . . . , owing to its physical orientation toward fundamental concepts and fundamental laws." As Einstein noted in his *Autobiographical Notes*⁸ written in 1946, Ernst Mach's *The Science of Mechanics* "shook this dogmatic faith" in "mechanics as the final basis of all physical thinking. . . . This book exercised a profound influence upon me in this regard while I was a student. I see Mach's greatness in his incorruptible skepticism and independence; in my younger years, however, Mach's epistemological position also influenced me very greatly (p. 21)."

As the long correspondence between those old friends shows, Besso remained a loyal Machist to the end. Thus, writing to Einstein on 8 December 1947, he still said: "As far as the history of science is concerned, it appears to me that Mach stands at the center of the development of the last 50 or 70 years." Is it not true, Besso also asked, "that this introduction [to Mach] fell into a phase of development of the young physicist [Einstein] when the Machist style of thinking pointed decisively at observables—perhaps even, indirectly, to clocks and meter sticks?"

Turning now to Einstein's crucial first paper on relativity in

Mach, Einstein, and the Search for Reality

1905, we can discern in it influences of many, partly contradictory, points of view—not surprising in a work of such originality by a young contributor. Elsewhere I have examined the effect—or lack of effect—on that paper of three contemporary physicists: H. A. Lorentz,¹⁴ Henri Poincaré,¹⁵ and August Föppl.¹ Here we may ask in what sense and to what extent Einstein's initial relativity paper of 1905 was imbued with the style of thinking associated with Ernst Mach and his followers—apart from the characteristics of clarity and independence, the two traits in Mach which Einstein always praised most.

In brief, the answer is that the Machist component—a strong component, even if not the whole story—shows up prominently in two related respects: first, by Einstein's insistence from the beginning of his relativity paper that the fundamental problems of physics cannot be understood until an epistemological analysis is carried out, particularly so with respect to the meaning of the conceptions of space and time¹⁶; and second, by Einstein's identification of reality with what is given by sensations, the “events,” rather than putting reality on a plane beyond or behind sense experience.

From the outset, the instrumentalist, and hence sensationist, views of measurement and of the concepts of space and time are strikingly evident. The key concept in the early part of the 1905 paper is introduced at the top of the third page in a straightforward way. Indeed, Leopold Infeld in his biography of Einstein called them “the simplest sentence[s] I have ever encountered in a scientific paper.” Einstein wrote: “We have to take into account that all our judgments in which time plays a part are always judgments of *simultaneous events*. If for instance I say, ‘that train arrived here at seven o'clock,’ I mean something like this: ‘The pointing of the small hand of my watch to seven and the arrival of the train are simultaneous events.’”¹⁷

The basic concept introduced here, one that overlaps almost entirely Mach's basic “elements,” is Einstein's concept of *events* (*Ereignisse*)—a word that recurs in Einstein's paper about a dozen times immediately following this citation. Transposed into Minkowski's later formulation of relativity, Einstein's “events” are the intersections of particular “world lines,” say that of the train and that of the clock. The time (*t* coordinate) of an event by itself has no operational meaning. As Einstein says: “The ‘time’ of an event is that which is given simultaneously with the event by a stationary

clock located at the place of the event" (p. 894). We can say that just as the *time* of an event assumes meaning only when it connects with our consciousness through sense experience (that is, when it is subjected to measurement-in-principle by means of a clock present at the same place), so also is the *place*, or space coordinate, of an event meaningful only if it enters our sensory experience while being subjected to measurement-in-principle (that is, by means of meter sticks present on that occasion at the same time).¹⁸

This was the kind of operationalist message which, for most of his readers, overshadowed all other philosophical aspects in Einstein's paper. His work was enthusiastically embraced by the groups who saw themselves as philosophical heirs of Mach, the Vienna Circle of neopositivists and its predecessors and related followers,¹⁹ providing a tremendous boost for the philosophy that had initially helped to nurture it. A typical response welcoming the relativity theory as "the victory over the metaphysics of absolutes in the conceptions of space and time . . . a mighty impulse for the development of the philosophical point of view of our time," was extended by J. Petzoldt in the inaugural session of the *Gesellschaft für Positivistische Philosophie* in Berlin, 11 November 1912.²⁰ Michele Besso, who had heard the message from Einstein before anyone else, had exclaimed: "In the setting of Minkowski's space-time framework, it was now first possible to carry through the thought which the great mathematician, Bernhard Riemann, had grasped: 'The space-time framework itself is formed by the events in it.'"²¹

To be sure, re-reading Einstein's paper with the wisdom of hindsight, as we shall do presently, we can find in it also very different trends, warning of the possibility that "reality" in the end is not going to be left identical with "events." There are premonitions that sensory experiences, in Einstein's later work, will not be regarded as the chief building blocks of the "world," that the laws of physics themselves will be seen to be built into the event-world as the undergirding structure "governing" the pattern of events.

Such precursors appear even earlier, in one of Einstein's early letters in the Archives. Addressed to his friend Marcel Grossmann, it is dated 14 April 1901, when Einstein believed he had found a connection between Newtonian forces and the forces of attraction between molecules: "It is a wonderful feeling to recognize the unity of a complex of appearances which, to direct sense experience, seem to be separate things." Already there is a hint here of the

Mach, Einstein, and the Search for Reality

high value that will be placed on intuited unity and the limited role seen for evident sense experience.

But all this was not yet ready to come into full view, even to the author. Taking the early papers as a whole, and in the context of the physics of the day, we find that Einstein's philosophical pilgrimage did start on the historic ground of positivism. Moreover, Einstein thought so himself, and confessed as much in letters to Ernst Mach.

The Einstein-Mach Letters

In the history of recent science, the relation between Einstein and Mach is an important topic that has begun to interest a number of scholars. Indeed, it is a drama of which we can sketch here four stages: Einstein's early acceptance of the main features of Mach's doctrine; the Einstein-Mach correspondence and meeting; the revelation in 1921 of Mach's unexpected and vigorous attack on Einstein's relativity theory; and Einstein's own further development of a philosophy of knowledge in which he rejected many, if not all, of his earlier Machist beliefs.

Happily, the correspondence is preserved at least in part. A few letters have been found, all from Einstein to Mach. Those of concern here are part of an exchange between 1909 and 1913, and they testify to Einstein's deeply felt attraction to Mach's viewpoint, just at a time when the mighty Mach himself—forty years senior to the young Einstein whose work was just becoming widely known—had for his part embraced the relativity theory publicly by writing in the second (1909) edition of *Conservation of Energy*: "I subscribe, then, to the principle of relativity, which is also firmly upheld in my *Mechanics* and *Wärmelehre*."²² In the first letter, Einstein writes from Berne on 9 August 1909. Having thanked Mach for sending him the book on the law of conservation of energy, he adds: "I know, of course, your main publications very well, of which I most admire your book on Mechanics. You have had such a strong influence upon the epistemological conceptions of the younger generation of physicists that even your opponents today, such as Planck, undoubtedly would have been called Mach followers by physicists of the kind that was typical a few decades ago."

It will be important for our analysis to remember that Planck was Einstein's earliest patron in scientific circles. It was Planck who, in 1905, as editor of the *Annalen der Physik*, received Einstein's first relativity paper and thereupon held a review seminar on the

paper in Berlin. Planck defended Einstein's work on relativity in public meetings from the beginning, and by 1913 had succeeded in persuading his German colleagues to invite Einstein to the Kaiser-Wilhelm-Gesellschaft in Berlin. With a polemical essay "Against the New Energetics" in 1896, he had made clear his position, and by 1909 Planck was one of the few opponents of Mach, and scientifically the most prominent one. He had just written a famous attack, *Die Einheit des physikalischen Weltbildes*. Far from accepting Mach's view that, as he put it, "Nothing is real except the perceptions, and all natural science is ultimately an economic adaptation of our ideas to our perceptions," Planck held to the entirely antithetical position that a basic aim of science is "the finding of a *fixed* world picture independent of the variation of time and people," or, more generally, "the complete liberation of the physical picture from the individuality of the separate intellects."²³ At least by implication in Einstein's remarks to Mach, he dissociated himself from allegiance to Planck's view. It may also not be irrelevant that just at that time Einstein, who since 1906 had been objecting to inconsistencies in Planck's quantum theory, was preparing his first major invited paper before a scientific congress, the eighty-first meeting of the Naturforscherversammlung, announced for September, 1909, in Salzburg. Einstein's paper called for a revision of Maxwell's theory to accommodate the probabilistic character of the emission of photons—none of which Planck could accept—and concluded: "To accept Planck's theory means, in my view, to throw out the bases of our [1905] theory of radiation."

Mach's reply to Einstein's first letter is now lost, but it must have come quickly, because eight days later Einstein sends an acknowledgment:

Berne, 17 August 1909. Your friendly letter gave me enormous pleasure. . . . I am very glad that you are pleased with the relativity theory. . . . Thanking you again for your friendly letter, I remain, your student [indeed: *Ihr Sie verehrender Schüler*], A. Einstein.

Einstein's next letter was written as physics professor in Prague, where Mach before him had been for twenty-eight years. The post had been offered to Einstein on the basis of recommendations of a faction (Lampa, Pick) who regarded themselves as faithful disciples of Mach. The letter was sent out about New Year's 1911-12, perhaps just before or after Einstein's sole (and, according to P. Frank's account in *Einstein, His Life and Times*, not very

Mach, Einstein, and the Search for Reality

successful) visit to Mach, and after the first progress toward the general relativity theory:

. . . I can't quite understand how Planck has so little understanding for your efforts. His stand to my [general relativity] theory is also one of refusal. But I can't take it amiss; so far, that one single epistemological argument is the only thing which I can bring forward in favor of my theory.

Here, Einstein is referring delicately to the Mach Principle, which he had been putting at the center of the developing theory.²⁴ Mach responded by sending Einstein a copy of one of his books, probably the *Analysis of Sensations*.

In the last of these letters to Mach (who was now seventy-five years old, and for some years had been paralyzed), Einstein writes from Zürich on 25 June 1913:

Recently you have probably received my new publication on Relativity and Gravitation which I have at last finished after unending labor and painful doubt. [This must have been the "Entwurf einer verallgemeinerten Relativitätstheorie und einer Theorie der Gravitation," written with Marcel Grossmann.²⁵] Next year at the solar eclipse it will turn out whether the light rays are bent by the sun, in other words whether the basic and fundamental assumption of the equivalence of the acceleration of the reference frame and of the gravitational field really holds. If so, then your inspired investigations into the foundations of mechanics—despite Planck's unjust criticism—will receive a splendid confirmation. For it is a necessary consequence that inertia has its origin in a kind of mutual interaction of bodies, fully in the sense of your critique of Newton's bucket experiment.²⁶

The Paths Diverge

The significant correspondence stops here, but Einstein's public and private avowals of his adherence to Mach's ideas continue for several years more. For example, there is his well-known, moving eulogy of Mach, published in 1916.¹³ In August, 1918, Einstein writes to Besso quite sternly about an apparent—and quite temporary—lapse in Besso's positivistic epistemology; it is an interesting letter, worth citing in full:

28 August 1918.

Dear Michele:

In your last letter I find, on re-reading, something which makes me angry: That speculation has proved itself to be superior to empiricism. You are thinking here about the development of relativity theory. However, I find that this development teaches something else, that it is prac-

GERALD HOLTON

tically the opposite, namely that a theory which wishes to deserve trust must be built upon generalizable facts.

Old examples: Chief postulates of thermodynamics [based] on impossibility of *perpetuum mobile*. Mechanics [based] on grasped [*ertasteten*] law of inertia. Kinetic gas theory [based] on equivalence of heat and mechanical energy (also historically). Special Relativity on the constancy of light velocity and Maxwell's equation for the vacuum, which in turn rest on empirical foundations. Relativity with respect to uniform [?] translation is a *fact of experience*.

General Reality: *Equivalence of inertial and gravitational mass*. Never has a truly useful and deep-going theory really been found purely speculatively. The nearest case is Maxwell's hypothesis concerning displacement current; there the problem was to do justice to the fact of light propagation. . . . With cordial greetings, your Albert. [Emphasis in the original]

Careful reading of this letter shows us that already here there is evidence of divergence between the conception of "fact" as understood by Einstein and "fact" as understood by a true Machist. The impossibility of the *perpetuum mobile*, the first law of Newton, the constancy of light velocity, the validity of Maxwell's equations, the equivalence of inertial and gravitational mass—none of these would have been called "facts of experience" by Mach. Indeed, Mach might have insisted that—to use one of his favorite battle words—it is evidence of "dogmatism" not to regard all these conceptual constructs as continually in need of probing re-examination; thus, Mach had written:²⁷

. . . for me, matter, time and space are still *problems*, to which, incidentally, the physicists (Lorentz, Einstein, Minkowski) are also slowly approaching.

Similar evidence of Einstein's gradual apostasy appears in a letter of 4 December 1919 to Paul Ehrenfest. Einstein writes:

I understand your difficulties with the development of relativity theory. They arise simply because you want to base the innovations of 1905 on epistemological grounds (nonexistence of the stagnant ether) instead of empirical grounds (equivalence of all inertial systems with respect to light).

Mach would have applauded Einstein's life-long suspicion of formal epistemological systems, but how strange would he have found this use of the word *empirical* to characterize the hypothesis of the equivalence of all inertial systems with respect to light! What we see forming slowly here is Einstein's view that the fundamental

Mach, Einstein, and the Search for Reality

role played by experience in the construction of fundamental physical theory is, after all, not through the “atom” of experience, not through the individual sensation or the protocol sentence, but through some creative digest or synthesis of “*die gesammten Erfahrungstatsachen*,” the *totality* of physical experience.²⁸ But all this was still hidden. Until Mach’s death, and for several years after, Einstein considered and declared himself a disciple of Mach.

In the meantime, however, unknown to Einstein and everyone else, a time bomb had been ticking away. Set in 1913, it went off in 1921, five years after Mach’s death, when Mach’s *The Principles of Physical Optics* was published at last. Mach’s preface was dated July, 1913—perhaps a few days or, at most, a few weeks after Mach had received Einstein’s last, enthusiastic letter and the article on general relativity theory. In a well-known passage in the preface (but one usually found in an inaccurate translation), Mach had written:

I am compelled, in what may be my last opportunity, to cancel my views [*Anschauungen*] of the relativity theory.

I gather from the publications which have reached me, and especially from my correspondence, that I am gradually becoming regarded as the forerunner of relativity. I am able even now to picture approximately what new expositions and interpretations many of the ideas expressed in my book on Mechanics will receive in the future from this point of view. It was to be expected that philosophers and physicists should carry on a crusade against me, for, as I have repeatedly observed, I was merely an unprejudiced rambler endowed with original ideas, in varied fields of knowledge. I must, however, as assuredly disclaim to be a forerunner of the relativists as I personally reject the atomistic doctrine of the present-day school, or church. The reason why, and the extent to which, I reject [*ablehne*] the present-day relativity theory, which I find to be growing more and more dogmatical, together with the particular reasons which have led me to such a view—considerations based on the physiology of the senses, epistemological doubts, and above all the insight resulting from my experiments—must remain to be treated in the sequel [a sequel which was never published].

Certainly, Einstein was deeply disappointed by this belated disclosure of Mach’s sudden dismissal of the relativity theory. Some months later, during a lecture on 6 April 1922 in Paris, in a discussion with the anti-Machist philosopher Emile Meyerson, Einstein allowed in a widely reported remark that Mach was “*un bon mécanicien*,” but a “*deplorable philosophe*.”²⁹

We can well understand that Mach’s rejection was at heart very

painful, the more so as it was somehow Einstein's tragic fate to have the contribution he most cared about rejected by the very men whose approval and understanding he would have most gladly had—a situation not unknown in the history of science. In addition to Mach, the list includes these four: *H. Poincaré*, who, to his death in 1912, only once deigned to mention Einstein's name in print, and then only to register an objection; *H. A. Lorentz*, who gave Einstein personally every possible encouragement—short of fully accepting the theory of relativity for himself; *Planck*, whose support of the special theory of relativity was unstinting, but who resisted Einstein's ideas on general relativity and the early quantum theory of radiation; and *A. A. Michelson*, who to the end of his days did not believe in relativity theory, and once said to Einstein that he was sorry that his own work may have helped to start this “monster.”³⁰

Soon Einstein's generosity again took the upper hand and resulted, from then to the end of his life, in many further personal testimonies to Mach's earlier influence.³¹ A detailed analysis was provided in Einstein's letter of 8 January 1948 to Besso:

As far as Mach is concerned, I wish to differentiate between Mach's influence in general and his influence on me. . . . Particularly in the *Mechanics* and the *Wärmelehre* he tried to show how conceptions arose out of experience. He 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 formation of concepts. In a way he thought that theories arise 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.

Now, as far as Mach's influence on my own development is concerned, it certainly was great. I remember very well that you drew my attention to his *Mechanics* and *Wärmelehre* during my first years of study, and that both books made a great impression on me. The extent to which they influenced my own work is, to say the truth, not clear to me. As far as I am conscious of it, the immediate influence of Hume on me was greater. . . . But, as I said, I am not able to analyze that which lies anchored in unconscious thought. It is interesting, by the way, that Mach rejected the special relativity theory passionately (he did not live to see the general relativity theory [in the developed form]). The theory

Mach, Einstein, and the Search for Reality

was, for him, inadmissibly speculative. He did not know that this speculative character belongs also to Newton's mechanics, and to every theory which thought is capable of. There exists only a gradual difference between theories, insofar as the chains of thought from fundamental concepts to empirically verifiable conclusions are of different lengths and complications.³²

Antipositivistic Component of Einstein's Work

Ernst Mach's harsh words in his 1913 preface leave a tantalizing mystery. Ludwig Mach's destruction of his father's papers has so far made it impossible to find out more about the "experiments" (possibly on the constancy of the velocity of light) at which Ernst Mach hinted. Since 1921, many speculations have been offered to explain Mach's remarks.³³ They all leave something to be desired. Yet, I believe, it is not so difficult to reconstruct the main reasons why Mach ended up rejecting the relativity theory. To put it very simply, Mach had recognized more and more clearly, years before Einstein did so himself, that Einstein had indeed fallen away from the faith, had left behind him the confines of Machist empirio-criticism.

The list of evidences is long. Here only a few examples can be given, the first from the 1905 relativity paper itself: What had made it really work was that it contained and combined elements based on two entirely different philosophies of science—not merely the empiricist-operationist component, but the courageous initial postulation, in the second paragraph, of two thematic hypotheses (one on the constancy of light velocity and the other on the extension of the principle of relativity to all branches of physics), two postulates for which there was and can be no direct empirical confirmation.

For a long time, Einstein did not draw attention to this feature. In a lecture at King's College, London, in 1921, just before the posthumous publication of Mach's attack, Einstein still was protesting that the origin of relativity theory lay in the facts of direct experience:

. . . I am anxious to draw attention to the fact that this theory is not speculative in origin; it owes its invention entirely to the desire to make physical theory fit observed fact as well as possible. We have here no revolutionary act, but the natural continuation of a line that can be traced through centuries. The abandonment of certain notions connected with space, time, and motion, hitherto treated as fundamentals, must not be regarded as arbitrary, but only as conditioned by observed facts.³⁴

GERALD HOLTON

By June, 1933, however, when Einstein returned to England to give the Herbert Spencer Lecture at Oxford entitled "On the Method of Theoretical Physics," the more complex epistemology that was in fact inherent in his work from the beginning had begun to be expressed. He opened this lecture with the significant sentence: "If you want to find out anything from the theoretical physicists about the methods they use, I advise you to stick closely to one principle: Don't listen to their words, fix your attention on their deeds." He went on to divide the tasks of experience and reason in a very different way from that advocated in his earlier visit to England:

We are concerned with the eternal antithesis between the two inseparable components of our knowledge, the empirical and the rational. . . . The structure of the system is the work of reason; the empirical contents and their mutual relations must find their representation in the conclusions of the theory. In the possibility of such a representation lie the sole value and justification of the whole system, and especially the concepts and fundamental principles which underlie it. Apart from that, these latter are free inventions of the human intellect, which cannot be justified either by the nature of that intellect or in any other fashion *a priori*.

In the summary of this section, he draws attention to the "purely fictitious character of the fundamentals of scientific theory." It is this penetrating insight which Mach must have smelled out much earlier and dismissed as "dogmatism."

Indeed, Einstein, in his 1933 Spencer Lecture—widely read, as were and still are so many of his essays—castigates the old view that "the fundamental concepts and postulates of physics were not in the logical sense inventions of the human mind but could be deduced from experience by 'abstraction'—that is to say, by logical means. A clear recognition of the erroneousness of this notion really only came with the general theory of relativity."

Einstein ends this discussion with the enunciation of his current credo, so far from that he had expressed earlier:

Nature is the realization of the simplest conceivable mathematical ideas. I am convinced that we can discover, by means of purely mathematical constructions, those concepts and those lawful connections between them which furnish the key to the understanding of natural phenomena. Experience may suggest the appropriate mathematical concepts, but they most certainly cannot be deduced from it. Experience remains, of course, the sole criterion of physical utility of a mathematical construction. But the creative principle resides in mathematics. In a certain sense, therefore, I hold it true that pure thought can grasp reality, as the ancients dreamed.³⁵

Mach, Einstein, and the Search for Reality

Technically, Einstein was now at—or rather just past—the mid-stage of his pilgrimage. He had long ago abandoned his youthful allegiance to a primitive phenomenism that Mach would have commended. In the first of the two passages just cited and others like it, he had gone on to a more refined form of phenomenism which many of the logical positivists could still accept. He has, however, gone beyond it in the second passage, turning toward interests that we shall see later to have matured into clearly meta-physical conceptions.

Later, Einstein himself stressed the key role of what we have called thematic rather than phenomonic elements³⁶—and thereby he fixed the early date at which, in retrospect, he found this need to arise in his earliest work. Thus he wrote in his *Autobiographical Notes* of 1946 that “shortly after 1900 . . . I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a *universal formal principle* could lead us to assured results.”³⁷

Another example of evidence of the undercurrent of disengagement from a Machist position is an early one: It comes from Einstein’s article on relativity in the 1907 *Jahrbuch der Radioaktivität und Elektronik* (Vol. 4, No. 4), where Einstein responds, after a year’s silence, to W. Kaufmann’s paper in the *Annalen der Physik* (Vol. 19, 1906). That paper had been the first publication in the *Annalen* to mention Einstein’s work on the relativity theory, published there the previous year. Coming from the eminent experimental physicist Kaufmann, it had been most significant that this very first discussion was announced as a categorical, experimental disproof of Einstein’s theory. Kaufmann had begun his attack with the devastating summary:

I anticipate right here the general result of the measurements to be described in the following: *the measurement results are not compatible with the Lorentz-Einsteinian fundamental assumption.*³⁸

Einstein could not have known that Kaufmann’s equipment was inadequate. Indeed, it took ten years for this to be fully realized, through the work of Guye and Lavanchy in 1916. So in his discussion of 1907, Einstein had to acknowledge that there seemed to be small but significant differences between Kaufmann’s results and Einstein’s predictions. He agreed that Kaufmann’s calculations seemed to be free of error, but “whether there is an unsuspected

systematic error or whether the foundations of relativity theory do not correspond with the facts one will be able to decide with certainty only if a great variety of observational material is at hand.”

Despite this prophetic remark, Einstein does not rest his case on it. On the contrary, he has a very different, and what for his time and situation must have been a very daring, point to make: He acknowledges that the theories of electron motion given earlier by Abraham and by Bucherer do give predictions considerably closer to the experimental results of Kaufmann. But Einstein refuses to let the “facts” decide the matter: “In my opinion both theories have a rather small probability, because their fundamental assumptions concerning the mass of moving electrons are not explainable in terms of the theoretical systems which embrace a greater complex of phenomena.”³⁹

This is the characteristic position—the crucial difference between Einstein and those who make the correspondence with experimental fact the chief deciding factor for or against a theory: Even though the “experimental facts” at that time very clearly seemed to favor the theory of his opponents rather than his own, he finds the *ad hoc* character of their theories more significant and objectionable than an apparent disagreement between his theory and their “facts.”⁴⁰

So already in this 1907 article—which, incidentally, Einstein mentions in his postcard of 17 August 1909 to Ernst Mach, with a remark regretting that he has no more reprints for distribution—we have explicit evidence of a hardening of Einstein against the epistemological priority of experiment, not to speak of sensory experience. In the years that followed, Einstein more and more openly put the consistency of a simple and convincing theory or of a thematic conception higher in importance than the latest news from the laboratory—and again and again he turned out to be right.

Thus, only a few months after Einstein had written in his fourth letter to Mach that the solar eclipse experiment will decide “whether the basic and fundamental assumption of the equivalence of the acceleration of the reference frame and of the gravitational field really holds,” Einstein writes to Besso in a very different vein (in March 1914), before the first, ill-fated eclipse expedition was scheduled to test the conclusions of the preliminary version of the general relativity theory: “Now I am fully satisfied, and I do not doubt any more the correctness of the whole system, may the observation of the eclipse succeed or not. The sense of the thing [*die*

Mach, Einstein, and the Search for Reality

Vernunft der Sache] is too evident." And later, commenting on the fact that there remains up to 10 per cent discrepancy between the measured deviation of light owing to the sun's field and the calculated effect based on the general relativity theory: "For the expert, this thing is not particularly important, because the main significance of the theory does not lie in the verification of little effects, but rather in the great simplification of the theoretical basis of physics as a whole."⁴¹ Or again, in Einstein's "Notes on the Origin of the General Theory of Relativity,"⁴² he reports that he "was in the highest degree amazed" by the existence of the equivalence between inertial and gravitational mass, but that he "had no serious doubts about its strict validity, even without knowing the results of the admirable experiment of Eötvös."

The same point is made again in a revealing account given by Einstein's student, Ilse Rosenthal-Schneider. In a manuscript "Reminiscences of Conversation with Einstein," dated 23 July 1957, she reports:

Once when I was with Einstein in order to read with him a work that contained many objections against his theory . . . he suddenly interrupted the discussion of the book, reached for a telegram that was lying on the windowsill, and handed it to me with the words, "Here, this will perhaps interest you." It was Eddington's cable with the results of measurement of the eclipse expedition [1919]. When I was giving expression to my joy that the results coincided with his calculations, he said quite unmoved, "But I knew that the theory is correct"; and when I asked, what if there had been no confirmation of his prediction, he countered: "Then I would have been sorry for the dear Lord—the theory is correct."⁴³

Minkowski's "World" and the World of Sensations

The third major point at which Mach, if not Einstein himself, must have seen that their paths were diverging is the development of relativity theory into the geometry of the four-dimensional space-time continuum, begun in 1907 by the mathematician H. Minkowski (who, incidentally, had had Einstein as a student in Zürich). Indeed, it was through Minkowski's semipopular lecture, "Space and Time," on 21 September 1908 at the eightieth meeting of the *Naturforscherversammlung*,⁴⁴ that a number of scientists first became intrigued with relativity theory. We have several indications that Mach, too, was both interested in and concerned about the introduction of four-dimensional geometry into physics (in Mach's cor-

respondence around 1910, for example, with A. Föppl); according to F. Herneck,⁴⁵ Ernst Mach specially invited the young Viennese physicist Philipp Frank to visit him “in order to find out more about the relativity theory, above all about the use of four-dimensional geometry.” As a result, Frank, who had recently finished his studies under Ludwig Boltzmann and had begun to publish noteworthy contributions to relativity, published the “presentation of Einstein’s theory to which Mach gave his assent” under the title “Das Relativitätsprinzip und die Darstellung der physikalischen Erscheinungen im vierdimensionalen Raum.”⁴⁶ It is an attempt, addressed to readers “who do not master modern mathematical methods,” to show that Minkowski’s work brings out the “empirical facts far more clearly by the use of four-dimensional world lines.” The essay ends with the reassuring conclusion: “In this four-dimensional world the facts of experience can be presented more adequately than in three-dimensional space, where always only an arbitrary and one-sided projection is pictured.”

Following Minkowski’s own papers on the whole, Frank’s treatment can make it nevertheless still appear that in most respects the time dimension is equivalent to the space dimensions. Thereby one could think that Minkowski’s treatment based itself not only on a functional and operational interconnection of space and time, but also—fully in accord with Mach’s own views—on the primacy of ordinary, “experienced” space and time in the relativistic description of phenomena.

Perhaps as a result of this presentation, Mach invoked the names of Lorentz, Einstein, and Minkowski in his reply of 1910 to Planck’s first attack, citing them as physicists “who are moving closer to the problems of matter, space, and time.” Already a year earlier, Mach seems to have been hospitable to Minkowski’s presentation, although not without reservations. Mach wrote in the 1909 edition of *Conservation of Energy*²²: “Space and time are here conceived not as independent entities, but as forms of the dependence of the phenomena on one another”; he also added a reference to Minkowski’s lecture of 1908.⁴⁴ But a few lines earlier, Mach had written: “Spaces of many dimensions seem to me not so essential for physics. I would only uphold them if things of thought [*Gedankendinge*] like atoms are maintained to be indispensable, and if, then, also the freedom of working hypotheses is upheld.”

It was correctly pointed out by C. B. Weinberg⁴⁷ that Mach may eventually have had two sources of suspicion against the Minkow-

Mach, Einstein, and the Search for Reality

skian form of relativity theory. As was noted above, Mach regarded the fundamental notions of mechanics as problems to be continually discussed with maximum openness within the frame of empiricism, rather than as questions that can be solved and settled—as the relativists, seemingly dogmatic and sure of themselves, were in his opinion more and more inclined to do. In addition, Mach held that the questions of physics were to be studied in a broader setting, encompassing biology and psychophysiology. Thus Mach wrote: “Physics is not the entire world; biology is there too, and belongs essentially to the world picture.”⁴⁸

But I see also a third reason for Mach’s eventual antagonism against such conceptions as Minkowski’s (unless one restricted their application to “mere things of thought like atoms and molecules, which by their very nature can never be made the objects of sensuous contemplations”⁴⁹). If one takes Minkowski’s essay seriously—for example, the abandonment of space and time separately, with identity granted only to “a kind of union of the two”—one must recognize that it entails the abandonment of the conceptions of experiential space and experiential time; and that is an attack on the very roots of sensations-physics, on the meaning of actual measurements. If identity, meaning, or “reality” lies in the four-dimensional space-time interval ds , one is dealing with a quantity which is hardly *denkökonomisch*, nor one that preserves the primacy of measurements in “real” space and time. Mach may well have seen the warning flag; and worse was soon to come, as we shall see at once.

In his exuberant lecture of 1908 (see Ref. 44), Minkowski had announced that “three-dimensional geometry becomes a chapter in four-dimensional physics. . . . Space and time are to fade away into the shadows, and only *eine Welt an sich* will subsist.” In this “world” the crucial innovation is the conception of the “*zeitartige Vektorelement*,” ds , defined as $(1/c) \sqrt{c^2 dt^2 - dx^2 - dy^2 - dz^2}$ with imaginary components. To Mach, the word *Element* had a crucial and very different meaning. As we saw in Schlick’s summary, elements were nothing less than the sensations and complexes of sensations of which the world consists and which completely define the world. Minkowski’s rendition of relativity theory was now revealing the need to move the ground of basic, elemental truths from the plane of direct experience in ordinary space and time to a mathematized, formalistic model of the world in a union of space and time that is not directly accessible to sensation—and, in this respect, is

reminiscent of absolute space and time concepts that Mach had called "metaphysical monsters."⁵⁰

Here, then, is an issue which, from the beginning, had separated Einstein and Mach even before they realized it. To the latter, the fundamental task of science was economic and descriptive; to the former, it was speculative-constructive and intuitive. Mach had once written: "If all the individual facts—all the individual phenomena, knowledge of which we desire—were immediately accessible to us, science would never have arisen."⁵¹ To this, with the forthrightness caused perhaps by his recent discovery of Mach's opposition, Einstein countered during his lecture in Paris of 6 April 1922: "Mach's system studies the existing relations between data of experience: for Mach, science is the totality of these relations. That point of view is wrong, and in fact what Mach has done is to make a catalog, not a system."⁵²

We are witnessing here an old conflict, one that has continued throughout the development of the sciences. Mach's phenomenalism brandished an undeniable and irresistible weapon for the critical re-evaluation of classical physics, and in this it seems to hark back to an ancient position that looked upon sensuous appearances as the beginning and end of scientific achievement. One can read Galileo in this light, when he urges the primary need of *description* for the fall of bodies, leaving "the causes" to be found out later. So one can understand (or rather, misunderstand) Newton, with his too-well-remembered remark: "I feign no hypotheses."⁵³ Kirchoff is in this tradition. Boltzmann wrote of him in 1888:

The aim is not to produce bold hypotheses as to the essence of matter, or to explain the movement of a body from that of molecules, but to present equations which, free from hypotheses, are as far as possible true and quantitatively correct correspondents of the phenomenal world, careless of the essence of things and forces. In his book on mechanics, Kirchoff will ban all metaphysical concepts, such as forces, the cause of a motion; he seeks only the equations which correspond so far as possible to observed motions.⁵⁴

And so could, and did, Einstein himself understand the Machist component of his own early work.

Phenomenalistic positivism in science has always been victorious, but only up to a very definite limit. It is the necessary sword for destroying old error, but it makes an inadequate plowshare for cultivating a new harvest. I find it exceedingly significant that Einstein saw this during the transition phase of partial disengage-

Mach, Einstein, and the Search for Reality

ment from the Machist philosophy. In the spring of 1917 Einstein wrote to Besso and mentioned a manuscript which Friedrich Adler had sent him. Einstein commented: "He rides Mach's poor horse to exhaustion." To this, Besso—the loyal Machist—responds on 5 May 1917: "As to Mach's little horse, we should not insult it; did it not make possible the infernal journey through the relativities? And who knows—in the case of the nasty quanta, it may also carry Don Quixote de la Einsta through it all!"

Einstein's answer of 13 May 1917 is revealing: "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 exterminate harmful vermin."

Toward a Rationalistic Realism

The rest of the pilgrimage is easy to reconstruct, as Einstein more and more openly and consciously turned Mach's doctrine upside down—minimizing rather than maximizing the role of actual details of experience, both at the beginning and at the end of scientific theory, and opting for a rationalism that almost inevitably would lead him to the conception of an objective, "real" world behind the phenomena to which our senses are exposed.

In the essay, "Maxwell's Influence on the Evolution of the Idea of Physical Reality" (1931), Einstein began with a sentence that could have been taken almost verbatim from Max Planck's attack on Mach in 1909, cited above: "The belief in an external world independent of the perceiving subject is the basis of all natural science." Again and again, in the period beginning with his work on the general relativity theory, Einstein insisted that between experience and reason, as well as between the world of sensory perception and the objective world, there are logically unbridgeable chasms. He characterized the efficacy of reason to grasp reality by the word *miraculous*; the very terminology in these statements would have been anathema to Mach.

We may well ask when and under what circumstances Einstein himself became aware of his change. Here again, we may turn for illumination to one of the hitherto unpublished letters, one written to his old friend, C. Lanczos, on 24 January 1938:

Coming from sceptical empiricism of somewhat the kind of Mach's, I was made, by the problem of gravitation, into a believing rationalist, that is, one who seeks the only trustworthy source of truth in mathematical

GERALD HOLTON

simplicity. The logically simple does not, of course, have to be physically true; but the physically true is logically simple, that is, it has unity at the foundation.

Indeed, all evidence points to the conclusion that Einstein's work on general relativity theory was crucial in his epistemological development. As he wrote later in "Physics and Reality" (1936): "the first aim of the general theory of relativity was the preliminary version which, while not meeting the requirements for constituting a closed system, could be connected in as simple a manner as possible with 'directly observed facts.'" But the aim, still apparent during the first years of correspondence with Mach, could not be achieved. In notes on the origin of the general relativity theory, Einstein reported:

I soon saw that the inclusion of non-linear transformation, as the principle of equivalence demanded, was inevitably fatal to the simple physical interpretation of the coordinate—i.e., that it could no longer be required that coordinate differences [ds] should signify direct results of measurement with ideal scales or clocks. I was much bothered by this piece of knowledge . . . [just as Mach must have been].

The solution of the above mentioned dilemma [from 1912 on] was therefore as follows: A physical significance attaches not to the differentials of the coordinates, but only to the Riemannian metric corresponding to them.⁵⁵

And this is precisely a chief result of the 1913 essay of Einstein and Grossmann,⁵⁶ the same paper which Einstein sent to Mach and discussed in his fourth letter. This result was the final consequence of the Minkowskian four-space representation—the sacrifice of the primacy of direct sense perception in constructing a physically significant system. It was the choice that Einstein had to make—against fidelity to a catalogue of individual operational experiences and in favor of fidelity to the ancient hope for a unity at the base of physical theory.⁵⁷

Enough has been written in other places to show the connections that existed between Einstein's scientific rationalism and his religious beliefs. Max Born summarized it in one sentence: "He believed in the power of reason to guess the laws according to which God has built the world."⁵⁸ Perhaps the best expression of this position by Einstein himself is to be found in his essay, "Über den gegenwärtigen Stand der Feld-Theorie," in the *Festschrift* of 1929 for Aurel Stodola.⁵⁹

Physical Theory has two ardent desires, to gather up as far as possible all

Mach, Einstein, and the Search for Reality

pertinent phenomena and their connections, and to help us not only to know *how* Nature is and *how* her transactions are carried through, but also to reach as far as possible the perhaps utopian and seemingly arrogant aim of knowing why Nature is *thus and not otherwise*. Here lies the highest satisfaction of a scientific person. . . . [On making deductions from a "fundamental hypothesis" such as that of the kinetic-molecular theory,] one experiences, so to speak, that God Himself could not have arranged those connections [between, for example, pressure, volume, and temperature] in any other way than that which factually exists, any more than it would be in His power to make the number 4 into a prime number. This is the promethean element of the scientific experience. . . . Here has always been for me the particular magic of scientific considerations; that is, as it were, the religious basis of scientific effort.

This fervor is indeed far from the kind of analysis which Einstein had made only a few years earlier. It is doubly far from the asceticism of his first philosophic mentor, Mach, who had written in his day book: "Colors, space, tones, etc. These are the only realities. Others do not exist."⁶⁰ It is, on the contrary, far closer to the rational realism of his first scientific mentor Planck, who had written: "The disjointed data of experience can never furnish a veritable science without the intelligent interference of a spirit actuated by faith. . . . We have a right to feel secure in surrendering to our belief in a philosophy of the world based upon a faith in the rational ordering of this world."⁶¹ Indeed, we note the philosophical kinship of Einstein's position with seventeenth-century natural philosophers—for example, with Johannes Kepler who, in the preface of the *Mysterium Cosmographicum*, announced that he wanted to find out concerning the number, positions, and motions of the planets, "why they are as they are, and not otherwise," and who wrote to Herwart in April, 1599, that, with regard to numbers and quantity, "our knowledge is of the same kind as God's, at least insofar as we can understand something of it in this mortal life."

Not unexpectedly, we find that during this period (around 1930) Einstein's non-scientific writings began to refer to religious questions much more frequently than before. There is a close relation between his epistemology, in which reality does not need to be validated by the individual's sensorium, and what he called "Cosmic religion,"⁶² defined as follows: "The individual feels the vanity of human desires and aims, and the nobility and marvelous order which are revealed in nature and in the world of thought. He feels the individual destiny as an imprisonment and seeks to experience the totality of existence as a unity full of significance."

GERALD HOLTON

Needless to say, Einstein's friends from earlier days sometimes had to be informed of his change of outlook in a blunt way. For example, Einstein wrote to Moritz Schlick on 28 November 1930:

In general your presentation fails to correspond to my conceptual style insofar as I find your whole orientation so to speak too positivistic. . . . I tell you straight out: Physics is the attempt at the conceptual construction of a model of the *real world* and of its lawful structure. To be sure, it [physics] must present exactly the empirical relations between those sense experiences to which we are open; but only *in this way* is it chained to them. . . . In short, I suffer under the (unsharp) separation of Reality of Experience and Reality of Being. . . .

You will be astonished about the "metaphysicist" Einstein. But every four- and two-legged animal is *de facto* in this sense metaphysicist. [Emphasis in the original]

Similarly, P. Frank, Einstein's early associate and later his biographer, reports that the realization of Einstein's true state of thought reached Frank in a most embarrassing way, at the congress of German physicists in Prague in 1929, just as Frank was delivering "an address in which I attacked the metaphysical position of the German physicists and defended the positivistic ideas of Mach." The very next speaker disagreed and showed Frank that he had been mistaken still to associate Einstein's views with that of Mach and himself. "He added that Einstein was entirely in accord with Planck's view that physical laws describe a reality in space and time that is independent of ourselves. At that time," Frank comments, "this presentation of Einstein's views took me very much by surprise."⁶³

In retrospect it is, of course, much easier to see the evidences that this change was being prepared. Einstein himself realized more and more clearly how closely he had moved to Planck, from whom he earlier dissociated himself in three of the four letters to Mach. At the celebration of Planck's sixtieth birthday, two years after Mach's death, Einstein made a moving speech in which, perhaps for the first time, he referred publicly to the Planck-Mach dispute and affirmed his belief that "there is no logical way to the discovery of these elementary laws. There is only the way of intuition" based on *Einfühlung* in experience.⁶⁴ The scientific dispute concerning the theory of radiation between Einstein and Planck, too, had been settled (in Einstein's favor) by a sequence of developments after 1911—for example, by Bohr's theory of radiation from gas atoms. As colleagues, Planck and Einstein saw each other regularly from 1913

Mach, Einstein, and the Search for Reality

on. Among evidences of the coincidence of these outlooks there is in the Einstein Archives a handwritten draft, written on or just before 17 April 1931 and intended as Einstein's introduction to Planck's hard-hitting article "Positivism and the Real External World."⁶⁵ In lauding Planck's article, Einstein concludes: "I presume I may add that both Planck's conception of the logical state of affairs as well as his subjective expectation concerning the later development of our science corresponds entirely with my own understanding."⁶⁶

This essay gave a clear exposition of Planck's (and one may assume, Einstein's) views, both in physics and in philosophy more generally. Thus Planck wrote there:

The essential point of the positivist theory is that there is no other source of knowledge except the straight and short way of perception through the senses. Positivism always holds strictly to that. Now, the two sentences: (1) *there is a real outer world which exists independently of our act of knowing* and (2) *the real outer world is not directly knowable* form together the cardinal hinge on which the whole structure of physical science turns. And yet there is a certain degree of contradiction between those two sentences. This fact discloses the presence of the irrational, or mystic, element which adheres to physical science as to every other branch of human knowledge. The effect of this is that a science is never in a position completely and exhaustively to solve the problem it has to face. We must accept that as a hard and fast, irrefutable fact, and this fact cannot be removed by a theory which restricts the scope of science at its very start. Therefore, we see the task of science arising before us as an incessant struggle toward a goal which will never be reached, because by its very nature it is unreachable. It is of a metaphysical character, and, as such, is always again and again beyond our achievement.⁶⁷

From then on, Einstein's and Planck's writings on these matters are often almost indistinguishable from each other. Thus, in an essay in honor of Bertrand Russell,⁶⁸ Einstein warns that the "fateful 'fear of metaphysics' . . . has come to be a malady of contemporary empiricistic philosophizing." On the other hand, in the numerous letters between the two old friends, Einstein and Besso, each to the very end touchingly and patiently tries to explain his position, and perhaps to change the other's. Thus, on 28 February 1952, Besso once more presents a way of making Mach's views again acceptable to Einstein. The latter, in answering on 20 March 1952, once more responds that the facts cannot lead to a deductive theory and, at most, can set the stage "for intuiting a general principle" as the basis of a deductive theory. A little later, Besso is gently scolded (in

Einstein's letter of 13 July 1952): "It appears that you do not take the four-dimensionality of reality seriously, but that instead you take the present to be the only reality. What you call 'world' is in physical terminology 'spacelike sections' for which the relativity theory—already the special theory—denies objective reality."

In the end, Einstein came to embrace the view which many, and perhaps he himself, thought earlier he had eliminated from physics in his basic 1905 paper on relativity theory: that there exists an external, objective, physical reality which we may hope to grasp—not directly, empirically, or logically, or with fullest certainty, but at least by an intuitive leap, one that is only guided by experience of the totality of sensible "facts." Events take place in a "real world," of which the space-time world of sensory experience, and even the world of multidimensional continua, are useful conceptions, but no more than that. For a scientist to change his philosophical beliefs so fundamentally is rare, but not unprecedented. Mach himself underwent a dramatic transformation quite early (from Kantian idealism, at about age seventeen or eighteen, according to Mach's autobiographical notes). We have noted that Ostwald changed twice, once to anti-atomism and then back to atomism. And strangely, Planck himself confessed in his 1910 attack on Mach (Ref. 23) that some twenty years earlier, near the beginning of his own career when Planck was in his late twenties (and Mach was in his late forties), he, too, had been counted "one of the decided followers of the Machist philosophy," as indeed is evident in Planck's early essay on the conservation of energy (1887).

In an unpublished fragment apparently intended as an additional critical reply to one of the essays in the collection *Albert Einstein, Philosopher-Scientist* (1949), Einstein returned once more—and quite scathingly—to deal with the opposition. The very words he used showed how complete was the change in his epistemology. Perhaps even without consciously remembering Planck's words in the attack on Mach of 1909 cited earlier—that a basic aim of science is "the complete liberation of the physical world picture from the individuality of the separate intellects"²³—Einstein refers to a "basic axiom" in his own thinking:

It is the postulation of a "real world" which so-to-speak liberates the "world" from the thinking and experiencing subject. The extreme positivists think that they can do without it; this seems to me to be an illusion, if they are not willing to renounce thought itself.

Mach, Einstein, and the Search for Reality

Einstein's final epistemological message was that the world of mere experience must be subjugated by and based in fundamental thought so general that it may be called cosmological in character. To be sure, modern philosophy did not gain thereby a major novel and finished corpus. Physicists the world over generally feel that today one must steer more or less a middle course in the area between, on the one hand, the Machist attachment to empirical data or heuristic proposals as the sole source of theory and, on the other, the aesthetic-mathematical attachment to persuasive internal harmony as the warrant of truth. Moreover, the old dichotomy between rationalism and empiricism is slowly being dissolved in new approaches.

Yet by going in his own philosophical development from one end of this range to the other, and by always stating forthrightly and with eloquence his redefined position, Einstein has helped us to define our own.

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1. Another recently published chapter for this study is the analysis of the probable sources of Einstein's first paper on relativity theory; see *American Scholar*, Vol. 37 (Winter, 1967), pp. 59-79.
2. These documents are mostly on deposit at the Archives of the Estate of Albert Einstein at Princeton; where not otherwise indicated, citations made here are from those documents. In studying and helping to order for scholarly purposes the materials in the Archives, I have benefited from and am grateful for the help received from the Trustees of the Albert Einstein Estate, and particularly from Miss Helen Dukas.

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GERALD HOLTON

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8. P. A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist* (Evanston, Ill., 1946).
9. *Die Mechanik in ihrer Entwicklung, historisch-kritisch dargestellt* (Leipzig, 1883).
10. In a special supplement on Ernst Mach in the journal *Neue Freie Presse* (Vienna), 12 June 1926.
11. Einstein himself, in a brief and telling analysis, published also in the *Neue Freie Presse* of Vienna on 12 June 1926 (the day of unveiling of a monument to Mach), wrote:

Ernst Mach's strongest driving force was a philosophical one: the dignity of all scientific concepts and statements rests solely in isolated experiences [*Einzelenerlebnisse*] to which the concepts refer. This fundamental proposition exerted mastery over him in all his research, and gave him the strength to examine the traditional fundamental concepts of physics (time, space, inertia) with an independence which at that time was unheard of.
12. Among many evidences of Mach's effectiveness, not the least are his five hundred or more publications (counting all editions—for example, seven editions of his *The Science of Mechanics* in German alone during his lifetime), as well as his large exchange of letters, books, and reprints (of which many important ones "carry the dedication of their authors," to cite the impressive catalogue of Mach's library by Theodor Ackermann, Munich, No. 634 [1959] and No. 636 [1960]). A glimpse of Mach's effect on those near him was furnished by William James, who in 1882 heard Mach give a "beautiful" lecture in Prague. Mach received James "with open arms. . . . Mach came to my hotel and I spent four hours walking and supping with him at his club, an unforgettable conversation. I don't think anyone ever gave me so strong an impression of pure intellectual genius. He apparently has read everything and thought about everything, and has an absolute simplicity of manner and winningness of smile when his face lights up, that are charming." From James's letter, in Gay Wilson Allen, *William James, a Biography* (New York, 1967), p. 249.

The topicality of Mach's early speculations on what is now part of General Relativity Theory is attested by the large number of continuing contributions on the Mach Principle. Beyond that, Mach's influence today

Mach, Einstein, and the Search for Reality

is still strong in scientific thinking, though few are as explicit and forthright as the distinguished physicist R. H. Dicke of Princeton University in his recent, technical book, *The Theoretical Significance of Experimental Relativity* ([London, 1964] pp. vii-viii): "I was curious to know how many other reasonable theories [in addition to General Relativity] would be supported by the same facts. . . . The reason for limiting the class of theories in this way is to be found in matters of philosophy, not in the observations. Foremost among these considerations was the philosophy of Bishop Berkeley and E. Mach. . . . The philosophy of Berkeley and Mach always lurked in the background and influenced all of my thoughts."

13. Albert Einstein, "Ernst Mach," *Physikalische Zeitschrift*, Vol. 17 (1916), p. 2.
14. Gerald Holton, "On the Origins of the Special Theory of Relativity," *American Journal of Physics*, Vol. 28 (October, 1960), pp. 627-36.
15. Gerald Holton, "Note on the Thematic Analysis of Science: The Case of Poincaré and Relativity," *Melanges Koyré* (Paris, 1964).
16. For evidences that this insistence on prior epistemological analysis of conceptions of space and time are Machist rather than primarily derived from Hume and Kant (who had, however, also been influential), see Einstein's detailed rendition of Mach's critique of Newtonian space and time, in Ref. 13; his discussion of Mach in the *Autobiographical Notes*, pp. 27-29; and in Ref. 1.
17. Albert Einstein, "Zur Elektrodynamik bewegter Körper," *Annalen der Physik*, Vol. 17 (1905), p. 893.
18. See also P. Frank, in P. A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*, pp. 272-73: "The definition of simultaneity in the special theory of relativity is based on Mach's requirement that every statement in physics has to state relations between observable quantities. . . . There is no doubt that . . . Mach's requirement, the 'positivistic' requirement, was of great heuristic value to Einstein."
19. For example, see Philipp Frank, *Modern Science and Its Philosophy* (New York, 1955), pp. 61-89; V. Kraft, *The Vienna Circle* (New York, 1953); R. von Mises, *Ernst Mach und die Empiristische Wissenschaftsauffassung* (1938; printed as a fascicule of the series *Einheitswissenschaft*).
20. J. Petzoldt, "Gesellschaft für Positivistische Philosophie," reprinted in *Zeitschrift für Positivistische Philosophie*, Vol. 1 (1913), p. 4.

In that same speech, Petzoldt sounded a theme that became widely favored in the positivistic interpretation of the genesis of relativity theory—namely, that the relativity theory was developed in direct response to the puzzle posed by the results of the Michelson experiment:

Clarity of thinking is inseparable from knowledge of a sufficient number of individual cases for each of the concepts used in investigation. Therefore, the chief requirement of positivistic philosophy: greatest respect for the facts. The newest phase of theoretical physics gives us an exemplary case. There, one does not hesitate, for the sake of a single

experiment, to undertake a complete reconstruction. The Michelson experiment is the cause and chief support of this reconstruction, namely, the electrodynamic theory of relativity. To do justice to this experiment one has no scruples to submit the foundations of theoretical physics as it has hitherto existed, namely, Newtonian mechanics, to a profound transformation.

In his interesting essay "Das Verhältnis der Machschen Gedankenwelt zur Relativitätstheorie," published as an appendix in the eighth German edition of Mach's *The Science of Mechanics* in the year 1921, Petzoldt faithfully attempts to identify and discuss several Machist aspects of Einstein's relativity theory:

(1) The theory "in the end is based on the recognition of the coincidence of sensations; and therefore it is fully in accord with Mach's worldview, which may be best characterized as a relativistic positivism" (p. 516).

(2) Mach's works "produced the atmosphere without which Einstein's Relativity Theory would not have been possible" (p. 494), and in particular Mach's analysis of the equivalence of rotating reference objects in Newton's bucket experiment prepared for the next step, Einstein's "equivalence of relatively moving coordinate systems" (p. 495).

(3) Mach's principle of economy is said to be marvelously exhibited in Einstein's succinct and simple statements of the two fundamental hypotheses. The postulate of the equivalence of inertial coordinate systems deals with "the simplest case thinkable, which now also serves as a fundamental pillar for the General Theory. And Einstein chose also with relatively greatest simplicity the other basic postulate [constancy of light velocity]. . . . These are the foundations. Everything else is logical consequence" (pp. 497-98).

21. Letter of Besso to Einstein, 16 February 1939. Among many testimonies to the effect of Einstein on positivistic philosophies of science, see P. W. Bridgman, "Einstein's Theory and the Operational Point of View," *Albert Einstein: Philosopher-Scientist*, ed. P. A. Schilpp.

22. Ernst Mach, *History and Root of the Principle of the Conservation of Energy* (Chicago, 1911), translation by P. Jourdain of second edition (1909), p. 95. For a brief analysis of Mach's various expressions of adherence as well as reservations with respect to the principle of relativity, see H. Dingler, *Die Grundlagen der Machschen Philosophie* (Leipzig, 1924), pp. 73-86.

F. Herneck (*Phys. Blätter*, Vol. 17 [1961], p. 276) reports that P. Frank wrote him he had the impression during a discussion with Ernst Mach around 1910 that Mach "was fully in accord with Einstein's special relativity theory, and particularly with its philosophical basis."

23. Republished in M. Planck, *A Survey of Physical Theory* (New York, 1960), p. 24. We shall read later a reaffirmation of this position, in almost exactly the same words, but from another pen.

After Mach's rejoinder (*Scientia*, Vol. 7 [1910], p. 225), Planck wrote a second, much more angry essay, "Zur Machschen Theorie der physikalischen Erkenntnis," *Vierteljahrsschrift für wissenschaftliche Philosophie*,

Mach, Einstein, and the Search for Reality

- Vol. 34 (1910), p. 497. He ends as follows: "If the physicist wishes to further his science, he must be a Realist, not an Economist [in the sense of Mach's principle of economy]; that is, in the flux of appearances he must above all search for and unveil that which persists, is not transient, and is independent of human senses."
24. Later Einstein found that this procedure did not work; see *Ideas and Opinions* (New York, 1954), p. 286, and other publications. In a letter of 2 February 1954 to Felix Pirani, Einstein writes: "One shouldn't talk at all any longer of Mach's principle, in my opinion. It arose at a time when one thought that 'ponderable bodies' were the only physical reality and that in a theory all elements that are fully determined by them should be conscientiously avoided. I am quite aware of the fact that for a long time, I, too, was influenced by this fixed idea."
25. *Zeitschrift für Mathematik und physik*, Vol. 62 (1913), pp. 225-61.
26. For a further analysis and the full text of the four letters, see F. Herneck, *Forschungen und Fortschritte*, Vol. 37 (1963), pp. 239-43, and *Wissenschaftliche Zeitschrift der Friedrich-Schiller-Universität Jena*, Vol. 15 (1966), pp. 1-14; and H. Hönl, *Phys. Bl.*, Vol. 16 (1960), p. 571. Many other evidences, direct and indirect, have been published to show Mach's influence on Einstein prior to Mach's death in 1916. For example, recently a document has been found which shows that in 1911 Mach had participated in formulating and signing a manifesto calling for the founding of a society for the positivistic philosophy. Among the signers, together with Mach, we find Joseph Petzoldt, David Hilbert, Felix Klein, George Helm, Sigmund Freud, and Einstein. (See F. Herneck, *Physikalische Blätter*, Vol. 17 [1961], p. 276.)
27. *Physikalische Zeitschrift*, Vol. 11 (1910), p. 605.
28. See Albert Einstein, "Time, Space, and Gravitation" (1948), *Out of My Later Years* (New York, 1950). Einstein makes the distinction between constructive theories and "theories of principle." Einstein cites, as an example of the latter, the relativity theory, and the laws of thermodynamics. Such theories of principle, Einstein says, start with "empirically observed general properties of phenomena."
29. *Bull. Soc. Franc. Phil.*, Vol. 22 (Paris, 1922), p. 111. In his 1913 preface rejecting relativity, Mach expressed himself perhaps more impetuously and irascibly than he may have meant. Some evidence for this possibility is in Mach's letters to J. Petzoldt. On 27 April 1914 Mach wrote: "I have received the copy of the positivistic *Zeitschrift* which contains your article on relativity; I liked it not only because you copiously acknowledge my humble contributions with respect to that theme, but also in general." And on 1 May 1914 Mach writes—rather more incoherently—to Petzoldt: "The enclosed letter of Einstein [a copy of the last of Einstein's four letters, cited above] proves the penetration of positivistic philosophy into physics; you can be glad about it. A year ago, philosophy was altogether sheer nonsense. The details prove it. The paradox of the clock would not have been noticed by Einstein a year ago."

I thank Mr. John Blackmore for drawing my attention to the Mach-Petzoldt letters, and to Dr. H. Müller for providing copies from the Petzoldt Archive in Berlin.

30. R. S. Shankland, *American Journal of Physics*, Vol. 31 (1963), p. 56.
31. A typical example is a letter of 18 September 1930 to Armin Weiner: . . . I did not have a particularly important exchange of letters with Mach. However, Mach did have a considerable influence upon my development through his writings. Whether or to what extent my life's work was influenced thereby is impossible for me to find out. Mach occupied himself in his last years with the relativity theory, and in a preface to a late edition of one of his works even spoke out in rather sharp refusal against the relativity theory. However, there can be no doubt that this was a consequence of a lessening ability to take up [new ideas] owing to his age, for the whole direction of thought of this theory conforms with Mach's, so that Mach quite rightly is considered as a forerunner of general relativity theory. . . .

I thank Colonel Bern Dibner for making a copy of the letter available to me from the Archives of the Burndy Library in Norwalk, Connecticut. Among other hitherto unpublished letters in which Einstein indicated his indebtedness to Mach, we may cite one to A. Lampa, 9 December 1935:

. . . You speak about Mach as about a man who has gone into oblivion. I cannot believe that this corresponds to the facts since the philosophical orientation of the physicists today is rather close to that of Mach, a circumstance which rests not a little on the influence of Mach's writings. Moreover, practically everyone else shared Einstein's explicitly expressed opinion of the debt of relativity theory to Mach; thus H. Reichenbach wrote in 1921 (*Logos*, Vol. 10, p. 331): "Einstein's theory signifies the accomplishment of Mach's program." Even Hugo Dingler agreed: "[Mach's] criticism of the Newtonian conceptions of time and space served as a starting point for the relativity theory. . . . Not only Einstein's work, but even more recent developments, such as Heisenberg's quantum mechanics, have been inspired by the Machian philosophy." *Encyclopedia of the Social Sciences*, Vol. 9 (New York, 1933), p. 653. And H. E. Hering wrote an essay whose title is typical of many others: "Mach als Vorläufer des physikalischen Relativitätsprinzips," *Kölner Universitätszeitung*, Vol. 1 (January 17, 1920), pp. 3-4. I thank Dr. J. Blackmore for a copy of the article.

32. In the special supplement of *Neue Freie Presse* of Vienna on 12 June 1926, Einstein—then already disenchanted for some time with the Machist program—wrote immediately after the portion quoted in Reference 11: Philosophers and scientists have often criticized Mach, and correctly so, because he erased the logical independence of the concepts vis-à-vis the "sensations," [and] because he wanted to dissolve the Reality of Being, without whose postulation no physics is possible, in the Reality of Experience. . . .

There are additional resources, both published and unpublished, on the detailed aspects of the relation between Einstein and Mach, which, for lack of space, cannot be summarized here.

Mach, Einstein, and the Search for Reality

33. For example, by Einstein himself, by Joseph Petzoldt, and by Hugo Dingler (cf. H. Dingler, *Encyclopedia of the Social Sciences*, pp. 84-86). I assign relatively little weight to the possibility that the rift grew out of the difference between Einstein and Mach on atomism. Herneck provides the significant report that according to a letter from P. Frank, Mach was personally influenced by Dingler, whom Mach had praised in the 1912 edition of the *Mechanik* and who was from the beginning an opponent of relativity theory, becoming one of the most "embittered enemies" of Einstein (F. Herneck, *op. cit.* [Ref. 26], p. 14). The copies of letters from Dingler to Mach in the Ernst-Mach-Institute in Freiburg indicate Dingler's intentions; nevertheless, there remains a puzzle about Dingler's role which is worth investigating. It is significant that in his 1921 essay, Petzoldt (Ref. 20) devotes much space to a defense of Einstein's work against Dingler's attacks. See also Joachim Thiele's detailed analysis of Mach's Preface, in *NTM, Schriftenreihe für Geschichte der Naturwissenschaften, Technik und Medizin*, Vol. 2 (Leipzig, 1965), pp. 10-19.
34. "On the Theory of Relativity," *Mein Weltbild* (Amsterdam, 1934); republished in *Ideas and Opinions* (New York, 1954), p. 246. F. Herneck has given the texts of similar discussions on phonographic records by Einstein in 1921 and even in 1924; cf. *Forschungen und Fortschritte*, Vol. 40 (1966), pp. 133-34.
35. Quotations from "On the Method of Theoretical Physics," *Mein Weltbild* (1934), as reprinted in translation in *Ideas and Opinions*, pp. 270-76, except for correction of mistranslation of one line. There are a number of later lectures and essays in which the same point is made. See, for example, the lecture, "Physics and Reality" (1936, reprinted in *Ideas and Opinions*), which states that Mach's theory of knowledge is insufficient on account of the relative closeness between experience and the concepts which it uses; Einstein advocates going beyond this "phenomenological physics" to achieve a theory whose basis may be further removed from direct experience, but which in return has more "unity in the foundations." Or see *Autobiographical Notes*, p. 27: "In the choice of theories in the future," he indicates that the basic concepts and axioms will continue to "distance themselves from what is directly observable."
- Even as Einstein's views developed to encompass the "erlebbare, beobachtbare" facts as well as the "wild-spekulative" nature of theory, so did those of many of the philosophers of science who also had earlier started from a more strict Machist position. This growing modification of the original position, partly owing to "the growing understanding of the general theory of relativity," has been chronicled by P. Frank, for example, in "Einstein, Mach, and Logical Positivism," in P. A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*.
36. For a discussion of thematic and phenomonic elements in theory construction, see G. Holton, "The Thematic Imagination in Science," in G. Holton (ed.), *Science and Culture* (Boston, 1965).
37. P. A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*, p. 53. Em-

GERALD HOLTON

- phases added. On pp. 9-11, Einstein describes what may be a possible precursor of this attitude in his study of geometry as a child.
38. W. Kaufmann, "Concerning the Constitution of the Electron," *Annalen der Physik*, Vol. 19 (1906), p. 495. Emphasis in original.
 39. *Jahrbuch der Radioaktivität und Elektronik*, Vol. 4 (1907), p. 28. Shortly after Kaufmann's article appeared, M. Planck (in *Physikalische Zeitschrift*, Vol. 7 [1906], pp. 753-61) took it on himself publicly to defend Einstein's work in an analysis of Kaufmann's claim. He concluded that Kaufmann's data did not have sufficient precision for his claim. Incidentally, Planck tried to coin the term for the new theory that had not yet been named: "Relativtheorie."
 40. It should be remembered that Poincaré, with a much longer investment in attempts to fashion a theory of relativity, was quite ready to give in to the experimental "evidence." See Ref. 15.
 41. Carl Seelig, *Albert Einstein* (Zürich, 1960), p. 195.
 42. Albert Einstein, "Notes on the Origin of the General Theory of Relativity," *Mein Weltbild* (Amsterdam, 1934), reprinted in translation in *Ideas and Opinions* (New York, 1954), pp. 285-90.
 43. "Da könnt' mir halt der liebe Gott leid tun, die Theorie stimmt doch." This semi-serious remark of a person who was anything but sacrilegious indeed illuminates the whole style of a significant group of new physicists. P. A. M. Dirac, in *Scientific American*, Vol. 208 (May 1963), pp. 47-48, speaks about this, with special attention to the work of Schrödinger, a spirit close to that of his friend, Einstein, despite the ambivalence of the latter to the advances in quantum physics. We can do no better than quote *in extenso* from Dirac's account [pp. 46-47]:

Schrödinger worked from a more mathematical point of view, trying to find a beautiful theory for describing atomic events, and was helped by deBroglie's ideas of waves associated with particles. He was able to extend deBroglie's ideas and to get a very beautiful equation, known as Schrödinger's wave equation, for describing atomic processes. Schrödinger got this equation by pure thought, looking for some beautiful generalization of deBroglie's ideas, and not by keeping close to the experimental development of the subject in the way Heisenberg did.

I might tell you the story I heard from Schrödinger of how, when he first got the idea for this equation, he immediately applied it to the behavior of the electron in the hydrogen atom, and then he got results that did not agree with experiment. The disagreement arose because at that time it was not known that the electron has a spin. That, of course, was a great disappointment to Schrödinger, and it caused him to abandon the work for some months. Then he noticed that if he applied the theory in a more approximate way, not taking into account the refinements required by relativity, to this rough approximation his work was in agreement with observation. He published his first

Mach, Einstein, and the Search for Reality

paper with only this rough approximation, and in this way Schrödinger's wave equation was presented to the world. Afterward, of course, when people found out how to take into account correctly the spin of the electron the discrepancy between the results of applying Schrödinger's relativistic equation and the experiments was completely cleared up.

I think there is a moral to this story, namely, that it is more important to have beauty in one's equations than to have them fit experiment. If Schrödinger had been more confident of his work, he could have published it some months earlier, and he could have published a more accurate equation. That equation is now known as the Klein-Gordon equation, although it was really discovered by Schrödinger, and in fact was discovered by Schrödinger before he discovered his non-relativistic treatment of the hydrogen atom. It seems that if one is working from the point of view of getting beauty in one's equations, and if one has really a sound insight, one is on a sure line of progress. If there is not complete agreement between the results of one's work and experiment, one should not allow oneself to be too discouraged, because the discrepancy may well be due to minor features that are not properly taken into account and that will get cleared up with further developments of the theory. That is how quantum mechanics was discovered

44. Published several times—for example, by Teubner, Leipzig, 1909.
45. F. Herneck, *Physikalische Blätter*, Vol. 15 (1959), p. 565. P. Frank's remark is reported by F. Herneck, in *Ernst Mach*, ed. W. F. Merzkirch (Freiburg, 1967), p. 50.
46. *Zeitschrift für Physikalische Chemie* (1910), pp. 466-95.
47. *Mach's Empirio-Pragmatism in Physical Science* (Thesis, Columbia University, 1937).
48. Ernst Mach, *Scientia*, Vol. 7 (1910), p. 225.
49. *Space and Geometry* (1906), p. 138. Mach's attempts to speculate on the use of n-dimensional spaces for representing the configuration of such "mere things of thought"—the derogatory phrase also applied to absolute space and absolute motion in Newton—are found in his first major book, *Conservation of Energy* (first edition, 1872).
50. Cf. J. Petzoldt, "Verbietet die Relativitätstheorie Raum und Zeit als etwas Wirkliches zu denken?" *Verhandlungen der Deutschen Physikalischen Gesellschaft*, Nos. 21-24 (1918), pp. 189-201. Here, and again in his 1921 essay (Ref. 20), Petzoldt tries to protect Einstein from the charge—for example, that by Sommerfeld—that space and time no longer "are to be thought of as real."
51. Ernst Mach, *Conservation of Energy*, p. 54.
52. *Op. cit.* Ref. 29; also reported in "Einstein and the Philosophies of Kant and Mach," *Nature*, Vol. 112 (August, 1923), p. 253.
53. That Einstein did not so misunderstand Newton can be illustrated, for example, in a comment reported by C. B. Weinberg: "Dr. Einstein further

GERALD HOLTON

- maintained that Mach, as well as Newton, tacitly employs hypotheses—not recognizing their non-empirical foundations.” (Weinberg, *op. cit.*, p. 55.) For an example of Mach’s tacit presuppositions, see H. Dingler, *Encyclopedia of the Social Sciences*, pp. 69-71. Dingler also analyzed some of the non-empirical foundations of relativity theory in *Kritische Bemerkungen zu den Grundlagen der Relativitätstheorie* (Leipzig, 1921).
54. Cited by R. S. Cohen in his very useful essay in P. Schilpp (ed.), *The Philosophy of Rudolf Carnap* (LaSalle, Ill., 1963), p. 109. I am also grateful to Professor Cohen for a critique of parts of this paper in earlier form.
55. Albert Einstein, “Notes on the Origin of the General Relativity Theory,” pp. 288-89.
56. Ref. 25, pp. 230-31.
57. I am not touching in this essay on the effect of quantum mechanics on Einstein’s epistemological development; the chief reason is that while from his “heuristic” announcement of the value of a quantum theory in 1905 Einstein remained consistently skeptical about the “reality” of the quantum theory of radiation, this opinion only added to the growing realism stemming from his work on general relativity theory. In the end, he reached the same position in quantum physics as in relativity; cf. his letter of 7 September 1944 to Max Born: “In our scientific expectations we have become antipodes. You believe in the dice-playing God, and I in perfect rules of law in a world of something objectively existing, which I try to catch in a wildly speculative way.” (Reported by Max Born, *Universitas*, Vol. 8 [1965], p. 33.)
58. Max Born, “Physics and Relativity,” *Physics in My Generation* (London, 1956), p. 205.
59. *Orell Füssli Verlag* (Zürich and Leipzig, 1929), pp. 126-32. I am grateful to Professor C. Lanczos and Professor John Wheeler for pointing out this reference to me.
60. H. Dingler, *Die Grundlagen der Machschen Philosophie*, p. 98.
61. *The Philosophy of Physics* (New York, 1936), pp. 122, 125.
62. In “Religion and Science,” written for *The New York Times Magazine*, 9 November 1930; cf. *Mein Weltbild*, p. 39, and *Cosmic Religion* (New York, 1931), p. 48.
- Possible reasons for Einstein’s growing interest in these matters, partly related to the worsening political situation at the time, are discussed in P. Frank, *Einstein, His Life and Times*. It is noteworthy that while Einstein was quite unconcerned with religious matters during the period of his early scientific publications, he gradually returned later to a position closer to that at a very early age, when he reported he had felt a “deep religiosity. . . . It is quite clear to me that the religious paradise of youth . . . was a first attempt to free myself from the chains of the ‘merely personal.’” *Autobiographical Notes*, p. 5. For a discussion, see G. Holton, *The Graduate Journal*, Vol. 7 (Spring 1967), pp. 417-20.

Mach, Einstein, and the Search for Reality

63. P. Frank, *Einstein, His Life and Times* (New York, 1947), p. 215. Einstein's change of mind was, of course, not acceptable to a considerable circle of previously sympathetic scientists and philosophers. See for example P. W. Bridgman, "Einstein's Theory and the Operational Point of View," in P. A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*.
64. Originally entitled "Motiv des Forschens" (in *Zu Max Planck*, Planck's 60. *Geburtstag* [Karlsruhe, Müller, 1918]), the talk had a fate not untypical of many of Einstein's essays. It was reprinted without date or source, under the title "Prinzipien der Forschung," in *Mein Weltbild*, and again, in perhaps unauthorized extension and translation by James Murphy, as a preface to M. Planck, *Where Is Science Going?* (London, 1933). In an earlier appreciation of Planck in 1913, Einstein had written only very briefly about Planck's epistemology, merely lauding Planck's essay of 1896 against energetics, and not mentioning Mach.
65. *International Forum*, Vol. 1, Nos. 1-2 (1931).
66. Einstein sent his introduction to the editor of the journal on 17 April 1931, but it appears to have come too late for inclusion.
67. Max Planck, "Positivism and External Reality," *The International Forum*, Vol. 1 (Berlin 1931), Nos. 1-2, pp. 15-16. Emphasis in original.
68. In *The Philosophy of Bertrand Russell*, ed. P. Schilpp (Evanston, 1944), p. 289.