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Mach's Philosophical Use of the History of Science

Ernst Mach devoted a major part of his life to historicocritical investigations that are focused upon philosophical problems in science. The object of this paper is to consider how he made use of the history of science to illuminate problems in the philosophy of science that he encountered in his work as a physicist.[1]

Mach: Physicist

An examination of Mach's published papers, of which there are about two hundred, reveals that he was an ingenious experimentalist, a keen and original critic of the empirical foundations of science, and singularly alert to the value of exploring questions in those areas where physics, physiology, and psychology overlap. The importance of Mach's historical and criticoanalytical contributions has been stressed in the literature at the expense of his activity as a scientist. An appreciation of this side of his life can be achieved through a contextual analysis of his many experimental papers.

Mach's interest in physics was born of an insatiable and tender curiosity about the world of his immediate environment. Einstein wrote concerning Mach: "The unmediated pleasure of seeing and understanding, Spinoza's *amor dei intellectualis*, was so strongly predominant in him that to a ripe old age he peered into the world with the inquisitive eyes of a carefree child taking delight in the understanding of relationships." Einstein recognized that even in cases where Mach's scientific investigations were not based upon new principles, his work invariably exhibited "extraordinary experimental talent."[2]

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[1] A convenient source of information about Mach's life is K. D. Heller, *Ernst Mach, Wegbereiter der modernen Physik* (Vienna: Springer, 1964). For works by and about Mach see Joachim Thiele, "Ernst Mach—Bibliographie," *Centaurus*, 8 (1963), 189–237.

Mach was a physicist by training. He never wanted to be known professionally as anything but a physicist. Of course, his conception of what constitutes physics was broad from the start. In his teaching and research and in his professorial role he was not bound by conventional academic guidelines. His doctoral work at the University of Vienna was completed in 1860 with a study on electrical discharge and induction. As a privatdocent at the university he engaged in studies on the change of musical pitch and color resulting from motion, viz., the Doppler effect.[3] During the winter semester of 1861–62 he lectured on "Physics for Medical Students."[4] During the summer semester his course was entitled "The Principles of Mechanics." He was able to supplement his meager income at this time by delivering popular lectures on psychophysics, Helmholtz's theory of the sensation of tone, and optics.[5]

From 1864 to 1867 Mach was, in turn, professor of mathematics and professor of physics at the University of Graz. It was there that he developed a deep and permanent interest in psychophysiological investigations in acoustics and optics.[6] In 1865 he discovered what later was referred to as "Mach bands"—a phenomenon that relates the physiological effect of spatially distributed light stimuli to visual perception.[7]

From 1867 to 1895, the most productive period of his life, Mach occupied the chair for experimental physics at the Charles University in Prague. There he continued his experimental researches in physiological

[2] Albert Einstein, "Ernst Mach," *Physikalische Zeitschrift*, 17 (1916), 101–104.

[3] Mach's papers of 1860–62 on this subject were republished later as *Beiträge zur Doppler'schen Theorie der Ton- und Färbenänderung durch Bewegung* (Prague: Calve, 1873).

[4] These lectures formed the basis for Mach's *Compendium der Physik für Mediciner* (Vienna: Wilhelm Braumüller, 1863). Important aspects of Mach's early pro-atomistic views, as expressed in this work, are discussed in my paper "The Genesis of Mach's Early Views on Atomism," *Boston Studies in the Philosophy of Science*, vol. VI (Dordrecht: D. Reidel, 1970), pp. 79–106.

[5] "Aus Dr. Mach's Vorträgen über Psychophysik," *Oesterreichische Zeitschrift für praktische Heilkunde*, 9 (1863), 146–366 (text interrupted). *Zwei populäre Vorlesungen über musikalische Akustik* (Graz: Leuschner & Lubensky, 1865); *Einleitung in die Helmholtz'sche Musiktheorie* (Graz: Leuschner & Lubensky, 1866); *Zwei populäre Vorträge über Optik* (Graz: Leuschner & Lubensky, 1867).

[6] *Optisch-akustische Versuche. Die spectrale und stroboskopische Untersuchung tönender Körper* (Prague: Calve, 1873).

[7] See Floyd Ratliff, *Mach Bands: Quantitative Studies on Neural Networks in the Retina* (San Francisco: Holden-Day, 1965), which contains in English translation Mach's five classic papers on this subject, 1865–68, and the paper of 1906 in which he dealt with temporally varying light stimuli on visual perception.

physics and psychophysics, the most celebrated results of which were the papers of 1873–75 on the changes in kinesthetic sensation associated with physical movement, acceleration, and orientation of the human body.[8] A wide variety of optical experiments connected with refraction, interference, and polarization continued to hold his attention. He investigated the wave motion associated with mechanical, electrical, and optical phenomena. Especially influential were the novel techniques that were introduced by Mach and his students for the photographic study of wave propulsion and gas dynamics for supersonic gas jets and projectiles.[9]

Mach's active involvement in experimental physics thus covers a period of about 35 years: namely, from 1860, when he was 22, until 1895, the year in which he moved from Prague to Vienna to accept a newly created professorship at the university. As a scientist he possessed a rare independence of judgment that was not always appreciated by his colleagues. But even when scientists rejected Mach's philosophical views they respected his experimental insight and ingenuity. Wilhelm Ostwald wrote: "So clear and calculated a thinker as Ernst Mach was regarded as a visionary [*Phantast*], and it was not conceivable that a man who understood how to produce such good experimental work would want to practice nonsense [*Allotria*] which was so suspicious philosophically."[10] Arnold Sommerfeld called Mach a brilliant experimentalist but a peculiar theoretician who, in seeking to embrace the "physiological" and "psychical" in his physics, had to relegate the "physical" to a less pretentious level than physicists were accustomed to expect from a colleague.[11]

While Mach devoted substantial efforts to certain aspects of theoretical physics—notably mechanics, thermodynamics, optics, molecular spectra, wave propulsion, the theory of perception (optical and aural), and the sensation of orientation in the human body—in general he did not convince his contemporaries of the importance of his theoretical and critical deliberations. There were some exceptions. Referring to Mach's *Mechanik* of 1883 and the criticisms of Newton's views on space, time, and motion, Einstein wrote in 1916: "There you will find set forth brilliantly ideas

[8] *Grundlinien der Lehre von den Bewegungsempfindungen* (Leipzig: W. Engelmann, 1875).

[9] See Wolfgang Merzkirch, "Mach's Contribution to the Development of Gas Dynamics," *Boston Studies in the Philosophy of Science*, VI, 42–59.

[10] *Lebenslinien, Eine Selbstbiographie*, vol. 2 (Berlin: Klasing, 1927), p. 171.

[11] "Nekrolog auf Ernst Mach," *Jahrbuch der König. bay. Akad. der Wiss.* (Munich), 1917, pp. 58–67.

which by no means as yet have become the common property of physicists."[12]

In Vienna, Graz, and Prague Mach was known as a stimulating physics teacher and popular science lecturer. Beginning in 1887 he published a series of secondary school textbooks in physics. At about the same time demonstration apparatus designed by Mach became known in Germany and the Austro-Hungarian empire. His *Popular Scientific Lectures*, which first appeared in English in 1895, was available shortly thereafter in German, Italian, and Russian. The point that deserves emphasis, in the context of this discussion, is that Mach consistently wanted to be known as a physicist. That is, he looked upon himself as a scientist who undertook experimental and theoretical investigations from the point of view of a professional physicist. About this there can be no doubt.

Mach: Historian of Science

Next to Mach's dedication to scientific investigation was his lifelong interest in the history of science. As early as 1863, at the age of 25, he was convinced that his scientific curiosity could be nurtured and promoted best if he were to become a serious student of the history of scientific ideas and practice.[13] The initial stimulus for his involvement in the history of science was a practical one intimately related to his search for sound pedagogical techniques in the teaching of science. Particularly with advanced studies he felt that students should not be expected to accept, as self-evident, propositions which had cost several thousand years' labor of thought. In 1872 in his first historical monograph, *History and Root of the Principle of the Conservation of Energy*, published in Prague, he wrote: "There is only one way to [scientific] enlightenment: historical studies!"[14]

According to Mach it was the history of science and not the logical analysis of science that would enable the scientist to consider problems without developing an aversion to them. He suggested two ways of becoming reconciled with actuality: "Either one grows accustomed to the puzzles and they trouble one no more, or one learns to understand them by the help of history and to consider them calmly from that point of view."[15]

[12] "Ernst Mach," p. 102.

[13] *Beiträge zur Analyse der Empfindungen* (Jena: Gustav Fischer, 1886), p. 21; English edition, *The Analysis of Sensations* (New York: Dover, 1959), p. 30.

[14] *Die Geschichte und die Wurzel des Satzes von der Erhaltung der Arbeit*, 2nd ed. (Leipzig: J. A. Barth, 1909), p. 2; English edition, *History and Root of the Principle of the Conservation of Energy* (Chicago: Open Court, 1911), p. 16.

[15] "Man gewöhnt sich an die Räthsel und sie belästigen uns nicht weiter. Oder man

He felt that the essence of a "special" classical education for the investigator of nature "consists in the knowledge of the historical development of . . . science."[16] Many years later, in 1905, in his *Erkenntnis und Irrtum* Mach wrote that, without claiming to be a philosopher, the scientist has a strong urge to satisfy an almost insatiable curiosity about the origins, structure, process, and conceptual roots of his discipline.[17]

Mach's historicocritical aims were explored first in 1872 in his *History and Root* where, with the focus clearly on history, he rejected metaphysics and sought to highlight the principle of economy of thought. It was, he remarked later, a first attempt to undertake studies epistemologically from the standpoint of the physiology of sensation (*erkenntniskritische sinnesphysiologische Studien*).[18] In this little volume he opened up ideas which were explored in one way or another for the greater part of his life: causality, the atomic theory, the criticisms of Newtonian mechanics, the meaning and purpose of scientific theories, and the criticisms of physical reductionism, metaphysics, mechanism, and materialism.

All of these matters are examined *in extenso* in Mach's historical treatises on mechanics, optics, and heat theory.[19] If we had the opportunity to follow the arguments in these works we would discover that definite recurrent themes stand out. They derive from the way in which certain unique epistemological questions are formulated: How did we acquire our present scientific concepts? Why did they take a given form among scientists and not another form that may be logically more convincing and esthetically more acceptable? What were the circumstances of analogical adaptation that led to the acceptance of a given concept?

Such questions having been posed, and clothed historically, the dominant lessons that shine through Mach's deliberations are these: Science has an incredibly rich history. Its ideas are alive. Its concepts, laws, and theories are in constant flux. They are perennially under revision and re-

lernt sie an der Hand der Geschichte verstehen, um sie von da an ohne Hass zu betrachten." *Geschichte*, p. 1; *History and Root*, pp. 15–16.

[16] *Geschichte*, p. 3; *History and Root*, p. 18.

[17] *Erkenntnis und Irrtum. Skizzen zur Psychologie der Forschung* (Leipzig: J. A. Barth, 1905), p. v.

[18] *Geschichte*, Vorwort, p. 3.

[19] *Die Mechanik in ihrer Entwickelung historisch-kritisch dargestellt* (Leipzig: F. A. Brockhaus, 1883); English edition, *The Science of Mechanics* (LaSalle, Ill.: Open Court, 1960). *Die Prinzipien der physikalischen Optik, historisch und erkenntnispsychologisch entwickelt* (Leipzig: J. A. Barth, 1921); English edition, *The Principles of Physical Optics* (New York: Dover; originally published 1926). *Principien der Wärmelehre, historisch-kritisch entwickelt* (Leipzig: J. A. Barth, 1896).

formulation. The conceptual products of science, always incomplete, take on a form at any particular time which reflects the historical circumstances and the focus of attention of the particular investigator—now physicist, now physiologist, now psychologist. Strictly speaking, scientific constructs therefore disclose the mode of cognitive organization of experience even when they contribute essentially nothing new to what is known. Because of the virtual infinity of the potentially relevant subject matter on the one hand, and the many-faced ways of examining it on the other, the investigator necessarily falls back upon abstraction.

Mach recognized that scientists normally place considerable stress on internal logic and consistency, maximum comprehensiveness, simplicity, and so on. Nevertheless, when examined within the historical context, scientific concepts, laws, and theories do not exhibit the tidy logical features that are supposed to represent the traditional bench marks of science. Rather, what predominantly stands out is a strong element of historical fortuitousness. With the passage of time, what is accidentally (historically) acquired is converted into the philosophically argued. For this reason it becomes mandatory for the scientist to recognize and counteract the insidious gradual process by which scientific constructs come to be regarded as philosophically necessary rather than historically contingent.

Familiarity with the internal subtleties of this movement from contingency to necessity, thinks Mach, can serve as the point of departure for developing the analytical and methodological tools to clarify and purify the conceptual components of science. This is a plea for the critical, historical, and psychological exposure of the roots of science that will reveal metaphysical obscurities and expose one-sided (e.g., mechanical) views of physics. The success of Mach's philosophical enterprise, if we may call it that, rests upon the feasibility of using the history of science to illuminate specific problems to which Occam's razor can be applied to remove metaphysical ballast and inherited anthropomorphisms and ambiguities. The over-all aim is to banish from science (and philosophy) all conceptual categories that have no analogues in experience. Scientific entities are not to be multiplied unnecessarily.

Among Mach's historical monographs the *Science of Mechanics* of 1883 offers a sharp-witted and provocative study of the role played by historical circumstance in the formulation of scientific concepts. The pertinence of instinctive knowledge, the function of memory, the relation between the origin of an idea and its rank in science, the psychology of discovery contra

the logic of discovery, the place of induction and deduction in physics—all are explored in tangible historical terms.

The first two chapters treat the principles of statics and dynamics—in 343 pages. The over-all objective is to demonstrate that statics is prior to dynamics, historically speaking, but that logically or conceptually statics can be recognized as a limiting case of dynamics. We note that there is no attempt to cover the history of statics or dynamics in a systematic manner. Still Mach rarely misses an opportunity to probe into the furthest corner of some aspect of the history of statics or dynamics when and where it serves his purpose. The historical illumination of specific physical problems is being pursued. In the course of the analysis Mach makes evident the historical importance, for the development of mechanics, of the solution of problems in dynamics based on an appeal to static arguments and of the solution of problems in statics based on an appeal to dynamic arguments.

Here, as elsewhere, Mach is prying into what it means to say that one principle is more basic or fundamental than another. He is asking whether instinctive knowledge, which is assumed to be self-evident, is fundamentally different from clear knowledge known to have been learned by experience. To this end the analysis of the mental procedures of different investigators is instructive. For example, by what authority does one proceed (as Stevin did) from the general view to the specific case, while another proceeds (as Archimedes did) from the specific case to the general view. In reference to Daniel Bernoulli's demonstration, that the proposition of the composition of forces is a geometrical truth independent of physical experience, Mach aims to point out that Bernoulli has merely reduced what is easier to observe to what is more difficult to observe; and that is scarcely a convincing demonstration.

In other examples Mach attempts to show that a mania for proof can cover up spurious rigor and that an appeal to the higher authority of purely instinctive cognition provides, at most, fallible useful knowledge. Believing that no place should be given to proofs in science without an appeal to experience, he criticizes "proofs" that have led to a belief in necessity. Moreover, an attempt is made to indicate, historically, that priority discovery or enunciation of one principle over another is not related to primacy. Mach contends that primacy cannot be relegated to the chances of history; that greater generality of a principle does not necessarily render it more basic; and that certain principles, which are an extension in appli-

cation of statics or dynamics, are equally basic. In other words, "basic" has no absolute significance when divorced from the scientific context of a problem.

The sagacious approach to scientific investigation consists in knowing when to accept instinctive knowledge as a starting point and when to embark on an abstract examination of its contents. Nature, as directly observed, leaves an imprint which is largely uncomprehended, unanalyzed, and embedded in inarticulate thought. Consequently it is risky to rest content with instinctive knowledge no matter how heuristically valuable. It is always illuminating, Mach argues, to uncover the historical conditions of the origins of knowledge.

The extended application of the principles of mechanics in relation to their deductive development is treated in the third chapter of the *Science of Mechanics*—a model of pedagogical, logical, and historical writing. Here Mach sets out to demonstrate how each of an interrelated set of principles can be applied to the solution of specific problems in the most advantageous, most economical, most logically satisfying way. He shows for a whole family of principles—exclusion of the *perpetuum mobile*, center of gravity, virtual work, *vis viva*, d'Alembert's principle, Gauss's principle of least constraint, Maupertuis's principle of least action, Hamilton's principle—that each can be derived mathematically from any other, provided that sufficient mathematical resourcefulness and industriousness are exercised.

Evidently the above-mentioned principles are related in such a way that provided one of them is accepted as true, the others can be deduced by mathematical and logical procedures alone. But what constitutes the evidence for the one which is accepted as true? Ultimately it cannot be justified except as it gives suitable answers to problems in statics and dynamics. And how was the principle discovered initially? Mach's answer, illustrated historically, is that the roots of the most primitive of such principles lie in experience—e.g., that man has not been able to construct a machine to deliver unlimited quantities of accomplishment (work) without the exertion of effort. Mach insists that none of the properties of nature can be constructed with the help of so-called self-evident suppositions alone. The suppositions must be derived from experience.

In his examination of the formal developments of mechanics Mach takes his chance to unmask the theological, animistic, and mystical elements of science, as he sees them. From a logical, economical, and practi-

cal point of view he finds no convincing reasons for the physicist to defend or rationalize the historical legacy of mechanics. True, the study of the history of science demonstrates how plausible it is for the concepts of mechanics to occupy a prestigious place among the sciences. Yet Mach believes that the applicability of mechanics to the other sciences is severely limited. He doubts, in fact, that mechanical principles will be beneficial for understanding the phenomena of heat, light, and electricity. In psychology, thinks Mach, the use of mechanics is utterly mischievous. In any case we must be wary of pressing all aspects of science into an a priori conceived mechanics mold. Or any other.

To examine critically Mach's diverse writings as a whole is to become immersed in the workings of the mind of an unbridled physicist who was intent upon clarifying certain perplexities reflected in the science of his day. In the process of pursuing this goal he not only managed to do physics and to write history, but, incidentally, to develop his own metaphysics—although he would have denied it. As a young man it seems that Mach pondered a great deal about what characterizes physics and the task of the physicist vis-à-vis new branches of science that spring up outside of physics. Through historical studies he hoped that he would learn to know how the basic physical concepts of his day had come into being and that this would provide him with the necessary directives for his own work. Mach had not the disposition to engage in the study of a scientific problem merely because it was respectable within the community of his colleagues to do so. He puzzled so deeply about the course that his own investigations should take because he was disturbed about some of the conceptual foundations of physics which were being accepted without critical examination.

It should be clear from what has already been said that Mach's physics was not meant to be the practical testing ground for his philosophical (epistemological) deliberations. Rather, the specific epistemological questions that he formulated were the logical consequence of his intense preoccupation with physics as seen from within the context of a tenacious inquisitiveness about the historical tradition inherited from the past. The exclusive function that the history of science served for Mach was the immediate result of his own scientific investigations and not the product of philosophical deliberations concerning the principles or formulas that might be prescribed for that investigation. His methodological reflections were the outgrowth of the scientific research in which he was engaged most of the time. Certainly he was concerned far less with developing a scien

tific philosophy than he was with the solution of specific problems that arose in connection with his attempts to keep abreast of the advances of physics and related disciplines.

If Mach eventually became involved in historicocritical investigations that had a reach far beyond his initial teaching objectives, it must be underscored that these endeavors were not undertaken with the intent of engaging in the history of science per se. The history of science was conceived rather as an indispensable critical probe for gaining an appreciation and understanding of the nature of science itself. While it can be granted that Mach was not concerned in the least with narrative, or chronicle, or reconstructing what really happened (as some historians are) it would be inaccurate to conclude that he was oblivious to the high demands of historical scholarship. If his historical information seems erroneous or superficial in places we must evaluate his work against the state of the art at the time.

It is apparent that the historical perspective of Mach's work was not primarily chronological, biographical, or even topical. He obviously made no attempt to discuss the evolution of scientific thought and practice systematically. Nor were his works conceived on the pattern of the intellectual historian who concentrates on the history of scientific ideas. Experimentation and the role of instrumentation were treated as an integral part of the critical and historical account of science that Mach sought to depict. Mach was not interested in achieving comprehensiveness of subject matter over a given area. Nor was he given to an exploration of the over-all general framework of science in relation to the organizational, institutional, or societal circumstances. He did not discuss the structure of scientific revolutions. Rather, Mach's interest in history was focused upon specific concepts, problems, instruments, and theoretical constructs the circumstances and developmental history of which, in his opinion, would help the scientist to appreciate and understand in depth the rationale of his scientific inheritance. He took up problems case by case. He managed to formulate these with unusual clarity and without overloading the issues with unessentials. He wrote no history where he saw no problem. He even was reluctant to discuss a problem when he could not offer historical commentary that would illuminate some facet of the problem.

Mach: Philosopher of Science

We have seen that Mach wanted to be regarded professionally as a physicist and that he had a vested interest in the history of science in terms of

what it meant to him as a physicist. What can be said about Mach as a philosopher? His own answer to that question, without any equivocation, was that he did not want to be recognized as a philosopher. In 1886 he wrote: "I make no pretensions to the title of philosopher. I only seek to adopt in physics a point of view that need not be changed immediately on glancing over into the domain of another science; for, ultimately, all must form one whole."[20]

It is true that the specific questions Mach raised about science were essentially of a philosophical nature. Although he was never at ease with "philosophy" he was not at all averse to the examination of philosophical questions provided that such activity implied nothing more than "scientific epistemology," i.e., *erkenntnistheoretische Untersuchungen*. But we must be clear about what he understood by epistemology. In point of fact his methodological *programme*, like that of positivists in general, excluded questions that deal with the existential status of reality. This was accomplished by presupposing that experience in the form of sensations is the only category that is epistemologically meaningful.

In 1895, after having taught physics for 35 years, Mach accepted a chair in Vienna for the history and theory of the inductive sciences. We know from an examination of his correspondence that he chose this title for his professorship within the philosophical faculty in order to avoid what he disliked intensely, namely, being identified as a philosopher. When his critics referred to *die Machsche Philosophie* he wrote in 1905: "Above all there is no Machist philosophy. At most [there is] a scientific methodology and a psychology of knowledge [*Erkenntnispsychologie*]; and like all scientific theories both are provisional and imperfect efforts. I am not responsible for the philosophy which can be constructed from these with the help of extraneous ingredients. . . . The land of the transcendental is closed to me. And if I make the open confession that its inhabitants are not able at all to excite my curiosity, then you may estimate the wide abyss that exists between me and many philosophers. For this reason I already have declared explicitly that *I am by no means a philosopher, but only a scientist*. If nevertheless occasionally, and in a somewhat noisy way, I have been listed among the former then I am not responsible for this. Of course, I also do not want to be a scientist who blindly entrusts himself to the guidance of a single philosopher in the way that Molière's physician expected

[20] *Beiträge zur Analyse*, p. 21; *The Analysis of Sensations*, p. 30.

and demanded of his patients."[21] In a note of 1913, published posthumously, Mach remarked that both physicists and philosophers carried on a crusade against him at a time when he considered himself to be no more than an unprejudiced rambler with ideas of his own in various areas of knowledge.[22]

Call him what you please, Mach exerted considerable influence upon the physical thought of several generations of scientists who, as Einstein suggests, were stimulated to ask significant questions on reading his works: What characteristic objectives can be achieved by approaching physics in a certain way? To what extent are the general results of science true? What is essential, and what merely rests upon fortuitous history? Einstein says: "It is a fact that Mach's historicocritical writings . . . have exerted a great influence upon our generation of natural scientists. I even believe that those who consider themselves as adversaries of Mach scarcely know how much they, so to speak, have been born and bred to Mach's outlook."[23]

Nominally, it was not philosophy of science and it was not history of science that Mach wished to pursue; it was the history and *theory* of the *inductive* sciences. At least that was a title Mach felt he could live with while being engaged in what sounds to me like the history and philosophy of science. In fact, one is tempted to conclude that Mach is a submerged philosopher formulating and reformulating, or wishing he could formulate, a theory of knowledge that would appeal to scientists in general and not just to physicists—an ambitious undertaking in the days before the philosophy of science was an established discipline.

The *Erkenntnis und Irrtum* of 1905 supplies ample evidence of Mach's progressive drift from physics to philosophy of science by way of the history of science. This work is the most comprehensive analytical and systematic treatment of Mach's philosophical views—although it is seldom read and almost never referred to by historians of science. It contains little history of science. For a person intimately acquainted with Mach's historical works it is not difficult to relate his mature philosophical reflections in this work to his historical approach. Still, there are only hints, and it is best to go searching for the connections in his earlier works.

Mach was preoccupied with historicophilosophical problems for almost 50 years; and we know that he devoted himself to them without relin-

[21] *Erkenntnis und Irrtum*, pp. vii–viii.
[22] *Die Prinzipien der physikalischen Optik*, p. viii; *The Principles of Physical Optics*, p. viii.
[23] "Ernst Mach," p. 102.

quishing his enthusiasm for teaching or his concern with experimental physics. Mach's philosophy of science, if we may call it that, was dominated, as we have already seen, by the desire to explore in depth, with the aid of history, the epistemological roots of science; but he believed that this could not be accomplished meaningfully without examining the behavior of the scientist—hence Mach's insistence on the importance of the analysis of sensations, and of the fundamental relevance of psychology and physiology as a corrective to the prevailing mechanistic physicalism.

Mach was predominantly destructive of the official school philosophies of his time and he discovered that he occupied the unpopular position associated with radical and empirical skepticism, the renunciation of truth in any transcendental sense, and the support of a theory of knowledge based on biological behavior. To disclaim any intention of substituting positivism for the variegated interpretations of philosophy elaborated by Kant's idealist successors surely represented the road of least resistance for Mach. Granted that he did not want traditional philosophers to accept the task of defining the function of science or of explaining the results of science, it seems unreasonable to suppose—considering how much he wrote on methodological matters in science—that he underestimated the heuristic importance of such extrascientific activities for the intellectual life of the practicing scientist. If the strict separation of science and philosophy which Mach's thought leads to is taken for granted by most scientists and philosophers today this was not so in Mach's environment.

The ambiguous position of Mach is apparent. It is that of a physicist, engaged in psychophysiological investigations, espousing historical evidence to expound an antimetaphysical philosophy of science while disclaiming any deep interest in traditional philosophy and even rejecting positivism as a philosophical system. In view of such an outlandish congeries of attitudes it is hardly surprising to discover that Mach's contemporaries—scientists, historians, and philosophers—could not avoid taking sides while engaging in an evaluation of his writings. Positions of neutrality or indifference toward Mach were rare. They still are. In fact, it is well known that several persons radically revised their opinions about Mach's philosophy after their initial sympathetic fling with Machistic positivism.[24] For example, Planck and Einstein, in their early and productive years, were impressed favorably by Mach's sensitive perceptions. Later

[24] Schrödinger in his youth was attracted to Mach the philosopher, but his "guardian angel intervened . . . [and] nothing came of it." Erwin Schrödinger, *My View of the World* (Cambridge: Cambridge University Press, 1964), p. viii.

they qualified their enthusiasm for Mach's philosophy of science and eventually became quite critical as they more fully became aware of the long-range implications of so antimetaphysical and antirealistic a world view.[25]

In Mach's time physicists, at least before they turned into philosophers, exhibited a greater affinity for Mach's philosophy of science than philosophers. This is still true today. Perhaps philosophers of science can suggest what that signifies, if anything. It seems to imply that Mach was more of a physicist's philosopher than a philosopher's philosopher. That would be plausible, since Mach struggled so diligently to establish with certainty the line of demarcation between cognitive and noncognitive endeavors—between science and philosophy. Here, our principal concern is to continue to examine Mach's position as a historian-philosopher and to evaluate the pertinence of Mach's history of science for his philosophy of science.

Mach: Historian-Philosopher

A basic assumption undergirds every aspect of Mach's scientific thought: viz., that all of our knowledge concerning the world of phenomena is acquired through experience. Nature is composed of sensations as its elements. They supply the only possible immediate source of revelation for scientific information. Experience is homogeneous with respect to the elements of sensation. Whether these elements are designated as physical, physiological, or psychical, there are no antagonisms or antinomies between them.

Such is the domain of circumscription for human cognition within which Mach prefers to philosophize. He knows, of course, that the critics will expect him to furnish a rationale for rejecting the other traditional claims of knowledge. His response is always the same: that metaphysical pretensions to cognition can be ruled out of science because they are empty of meaningful content and because they merely serve to befuddle the real problems with which scientists struggle. No doubt about it—this is a circular argument. Nevertheless, Mach seems to believe that his epistemology furnishes a manageable policy of operation. History, he maintains, justifies his point of view.

The history of science, Mach believed, demonstrates that there are no sharp boundary lines separating the scientific from the nonscientific or

[25] For a discussion and evaluation of the differences in philosophical outlook between Mach and Planck see Erwin Hiebert, *The Conception of Thermodynamics in the Scientific Thought of Mach and Planck*, Wissenschaftlicher Bericht Nr. 5/68 (Freiburg im Breisgau: Ernst-Mach-Institut, 1968), pp. 1–106.

prescientific experience of man. Similarly, no sharp discontinuities exist between ordinary language and the highly theoretical language of science. The given world can be represented as a complex of interrelated sensations. The "given" embraces the object and the subject of the sensations: the observed and the observer, or the sensed and the senser. The dualism between subject and object disappears. The process of acquiring knowledge is structured biologically (psychophysiologically) and consists of adapting facts (*Tatsachen*) to thoughts (*Gedanken*) and of thoughts to other thoughts.[26]

According to Mach there is no such thing as Kant's *Ding-an-sich*, or at least no meaningful discourse can take place about such referents. It is an illusion to believe that a final "thing in itself" remains after all the qualities of a body have been subtracted from it. Bodies, for example, are mere mental symbols to represent the relatively permanent conjunction of elements of sensations—the conventional attributes like color and sound. The single "thing" with its many attributes is a protean pseudo-philosophical conception.

The so-called objects of our experience are thought symbols for complexes of elements (sensations). We need not know what is characteristically physical, what physiological, and what psychical among the components of experience. It suffices to discover the functional relations of the sensations to one another. To speak of something being physical means to designate only one method of cognitive organization. Everything turns on considering different ultimate variables and different relations of dependence. Thus for Mach, as it had been for Hume, the perceptions of the mind are roughly divided into two classes, being distinguished by the different degrees of their force and vivacity: first, the immediately experienced impressions (facts); and second, the ideas (thoughts), or the less lively perceptions rooted in the memory or imagination. Accordingly, the operations which constitute scientific understanding of the world are exhausted in providing relationships between matters of fact, between fact and ideas, and between ideas and other ideas.

The mind of man can organize, rearrange, reject, and synthesize what is given in experience, but deliberation about and manipulation of the empirically given cannot be relied upon to give new information about the world. This is not to say that it is pointless to predict how the world will

[26] *Erkenntnis und Irrtum*, "Anpassung der Gedanken an die Tatsachen und aneinander," pp. 164–182.

behave in the unknown, but rather that experience is the final judge about how the world in fact does behave in the unknown. With respect to our knowledge about the phenomenal world, experience is king. That king cannot be checkmated without putting an end to the game which scientists play.

Crucial for our evaluation of Mach's philosophical use of the history of science are his views on the role of the experiment in science. On such matters he presents a consistent view which correlates perfectly with his epistemology. As already intimated, it rests upon belief in the fundamental and constitutional uniformity in the method of obtaining valid knowledge for all areas of human endeavor, viz., by direct experience and by theoretical deliberation about experience. This does not mean that the sciences necessarily progress by a leveling process toward a unity which destroys the independent status of the different scientific disciplines. Quite to the contrary, Mach's scientific monism leaves no room for scientific reductionism; it is a monism of method.

What constitutes experimentation for Mach? There is no special *method* of investigation, discovery, or induction, in science. Rather, we recognize the substantial unity in the modes of scientific and everyday thought. Still we know that there will be enormous differences in the range of expertise and subtlety employed in the pursuit of one or another subject matter. Likewise, it is apparent that there will be striking contrasts in accomplishment for the separate branches of science, at various times, and under diverse environmental circumstances. It is these differences which must be studied and analyzed for what they reveal about the genesis of scientific constructs and ideas. It has been said often, at least since Auguste Comte, that science is a social phenomenon and that its state of organization and its composition hinge on the historical circumstances associated with its advancement. This is not what Mach had in mind. He wanted to demonstrate that the content of science as an intellectual inheritance depends upon the historical conditions under which the conceptual notions in the various sciences have developed.

The clue to fruitful experimentation rests upon a kind of operational bias strengthened by psychological and physical intuition. It represents the investigation and exploitation of functional dependencies that are *suspect*, and for which meaningful tests can be invented. And what is *suspect*? According to Mach: potentially, almost everything. Since there is no special method of scientific discovery the productive scientist will maintain an

attitude of maximum open-endedness in his search for the relevant functional dependencies. How much of nature should be placed under observation at one time? In such matters chance favors the prepared mind. In general it is wise not to draw the boundaries of a scientific investigation so broadly as to invite discouragement, but also not so narrowly as to confine the analysis to what is empty and aimless. The experimentalist should spend large fractions of his "experimenting time" in thinking about the most advantageous way to interrogate nature. The discussion of this subject comes up notably in Mach's writings under the heading of "thought experiments" (*Gedankenexperimente*). He asks: Who is the real experimenter? The so-called experimentalist operating with facts, or the so-called theoretician experimenting with concepts? The scientist can and must be both.[27]

What about the relationship of facts to hypotheses in the writings of Mach? Real, fixed, isolated facts exist only within our minds to be used as intellectual anchor points for building hypotheses. Reflection about these so-called facts and analysis of their conditions, parts (constituents), and consequences define the hypotheses and the conditions under which they are applicable. The hypotheses are heuristic devices that indicate the possible modes of testing our maneuvers within science; but more important, they motivate us toward other schemes of experimentation. The task which Mach set for himself in his historical treatises on mechanics, heat, and optics was to show from a critical and psychological standpoint how various ideas within these disciplines had been molded and transformed not only by the revelation of new facts but by reason of the views historically associated with them; and, further, how the general concepts of science developed from within the individual disciplines.[28]

The values that result from formulating hypotheses (as heuristic devices) are three: first, they *sometimes* reveal the correspondences that were suspected and predicted; second, they *more often* simply falsify the correspondences; third, they *most often* indicate something about a problem different from the one that was placed under investigation. Here is Mach's position on the third point: Concerning the conditions of the unknown we are not able to formulate ideas with sufficient clarity in relation to our

[27] Mach first discussed "Gedankenexperimente" in an article entitled "Über Gedankenexperimente," *Zeitschrift für den physikalischen und chemischen Unterricht*, 10 (1897), 1–5. The subject was explored more fully in *Erkenntnis und Irrtum*, pp. 183–200.

[28] See, for example, the Preface to *The Principles of Physical Optics*.

scientific objectives. So we invent temporary conditions that are conceivable or else familiar to us because of previous experience. On testing our conjectural schemes we most frequently discover something about approaching the problem from another point of view that hitherto had been unfamiliar to us. Moreover, we discover that not all of our formulated scientific problems can be solved, because they may turn out not to be problems at all. They may result from the nonsensical way in which they were posed. And thus it comes about that an experimental investigation (i.e., one in which there is experimentation with concepts or facts) leads to no new knowledge but leads the way to another mode of acquiring new knowledge.[29]

There is one other central pillar of Mach's scientific doctrine that will help us to understand how the history of science was pressed into the service of the philosophy of science. This is his principle of economy of thought, concerning which Charles S. Peirce said: "Dr. Mach, who has one of the best faults a philosopher of science can have, that of riding his horse to death, does just this with his principle of Economy in science."[30] In Mach's writings, economy of thought (*die Oekonomie der Wissenschaft*) shows up everywhere.[31]

The meaningful goal that science can set for itself is the simplest and most economical abstract expression of facts. It is suggested that whereas the events of nature are simply given (once), our schematic mental imitations identify "like events" in nature; that these "like events" exist with certain mutually dependent features only in our minds. In an essay on "the economical nature of physics" Mach expresses himself as follows: "Language, with its helpmate, conceptual thought, by fixing the essential and rejecting the unessential, constructs its rigid pictures of the fluid world on the plan of a mosaic, at a sacrifice of exactness and fidelity but with a saving of tools and labor."[32]

According to Mach, all communicable elements of science take advantage of economy in intellectual exertion. Scientific constructs, laws, and theories represent ordered factual information and experience. "It is the

[29] *Erkenntnis und Irrtum*, pp. 232–250.

[30] *Essays in the Philosophy of Science*, ed. V. Tomas (New York: Liberal Arts Press, 1957), p. 228.

[31] The principle of economy of thought is discussed in many places in Mach's writings but notably in *History and Root of the Principle of the Conservation of Energy*, *The Science of Mechanics*, *Principien der Wärmelehre*, and *Popular Scientific Lectures* (La Salle, Ill.: Open Court, 1943).

[32] *Popular Scientific Lectures*, p. 192.

object of science to replace, or save, experience, by the reproduction and anticipation of facts in thought. Memory is handier than experience, and often answers the same purpose."[33] This economical office of science not only relieves the memory; it renders superfluous the endless repetition of experiments.

The danger inherent in this biologically conditioned situation resides in the temptation to reify mental constructs like substance, force, and energy. The study of the history of science reveals that such constructs, originally provisional, in time and by successful application receive metaphysical sanctions that are virtually unassailable. Thus insulated from the ongoing scene of action of science, where criticism, revision, and rejection are the rule, these constructs acquire the status of logical necessity or receive acceptance as self-evident and intuitively known truths. For Mach there are no such invulnerable truths—at least not at a level of synthetic description that is so far removed from the phenomenological elements of pure sensation. Scientific constructs, laws, and theories never lose their provisional status.

We only begin to understand the duty that the principle of economy of thought has to perform within the historicophilosophical framework of Mach's ideas by describing, in his terms, what biological function the principle promotes. It has no ontological status. It is not a physical law. It is rather a description of the biological law that regulates the manner in which cognitive elements about the world are incorporated into man's thought. Mach claims, as Avenarius had done earlier, that the principle of economy of thought is but a description of animal behavior. The study of this behavior, i.e., the empirical study of history in the light of behavioral psychology, but liberated from metaphysical muddleheadedness, is the central task of the historian of science. The evolution of science thus becomes a special case of the larger biological process of self-preservation through mental adaptation.

In conclusion I recognize that perceptive critics will have no difficulty in pointing out that Mach does not treat the philosophy of science in a formal or methodical manner. He was not a systematic philosopher, and was not occupied with constructing scientific systems. There are in his works lacunae, as well as redundancies and inconsistencies; but Mach is never just marking time or filling in the historical details for some aspect of science unrelated to the methodological point he sets out to make. He

[33] *The Science of Mechanics*, p. 577.

simply claims to be exploring scientific puzzles and discovering that some of them vanish and take their places among the shadows of history.

A more serious objection to Mach's epistemological formulation of cognition than its nonsystematic character is that it violates his own philosophical position. Since he believes that empirical methods cannot be employed to establish the truth of any theory—and that includes a theory of knowledge—Mach would have to admit that his own epistemological formulation of the cognitive process rests upon philosophical presuppositions of some kind. But this is just what he denies. He claims that it is possible to analyze objectively the cognitive process in man through the empirical study of history.

It could be said that Mach should have learned that antimetaphysical protestations and all that goes with trying to establish an epistemology without overtly recognizing some philosophical presuppositions lead nowhere if not to metaphysics. Mach never conceded that he had to become a philosopher or metaphysician in order to rationalize his scientific position. Toward the end of his life he did become more tolerant about philosophy and even expressed appreciation for the fact that "a whole host of philosophers—positivists, critical empiricists, adherents of the philosophy of immanence and certain isolated scientists as well—have all, without any knowledge of one another's work, entered upon paths which, in spite of all their individual differences, converge almost towards one point."[34] Surely Mach, the positivist, who tried to restrict the data of his science to what is given in the elements of sensation, thereby showed his philosophical hand.

I have tried to explain how Mach's diverse investigations were the outcome of a search for the underlying foundations and meaning of scientific puzzlements which commanded his attention as a young physicist. The more Mach deliberated about these matters and the more he wrote in order to clarify them, the more his views crystallized and took on a dogmatic form. In doing so he had moved toward working out philosophical arguments which were no longer primarily focused on the historical explanation of scientific enigmas. Mach, the puzzled physicist who had turned historian, had been transfigured into a philosopher.

[34] *The Analysis of Sensations*, p. xli (Preface to the 4th edition of 1903). See also Mach's comments in the Preface to the 7th (1912) edition of *The Science of Mechanics*.