Ernst Mach as Teacher and Thinker

A textbook especially for medical students, demonstration apparatus for mechanics and optics, and publications in psychology, physiology and the history and theory of inductive science were among the activities of this physicist who gave equal weight to teaching and research.

by Otto Blüh

THE YEAR OF Ernst Mach's hundredth birthday, 1938, was the first occasion for commemorating his work. At that time the difficult political situation in Central Europe made any such event unfeasible. The members of the so-called "Vienna School" of neopositivism, who at their beginning had assumed the name of "Ernst Mach Society," had dispersed, and in Prague, where a program of lectures on Mach had been prepared, the celebrations had to be curtailed because of unrest in the spring of 1938. Spring of 1966 was the next opportunity for remembering Mach and his work, on the 50th anniversary of his death in 1916. In fact, the "Ernst-Mach-Institute" in Freiburg im Breisgau arranged an international conference on Mach, and last December the American Association for the Advancement of Science, with its Ernst Mach Symposium, also shared in honoring Mach's personality and work.

The 28-year postponement had its definite advantages. Any celebration in 1938 would have been a partisan affair and probably would have done more harm than good for the lasting memory of Mach. In the meantime we have gained a much better perspective and can appreciate Mach's work in its full extent. We should, today, be able to discuss his work objectively and even be prepared to admit its shortcomings.

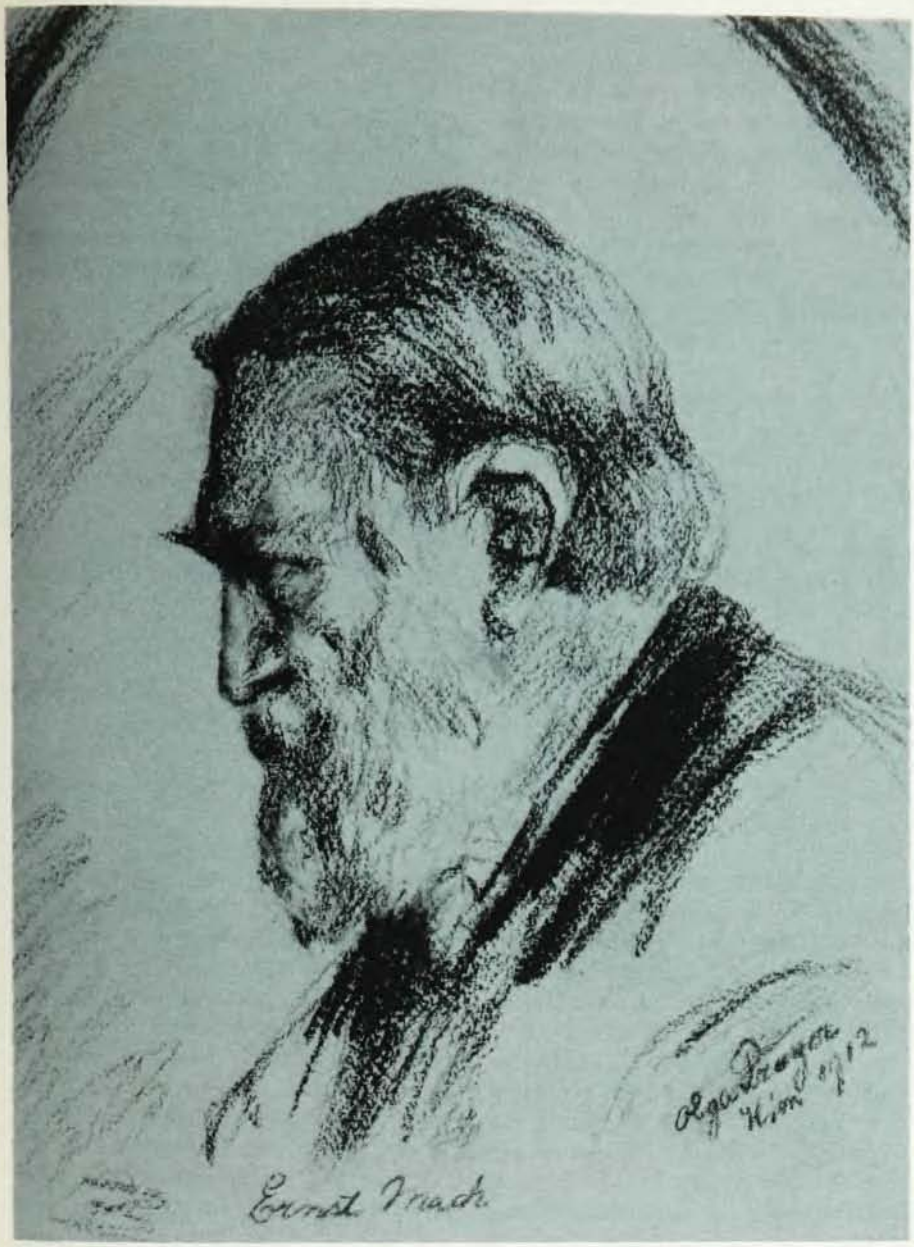
Mach's name has become familiar through the Mach number, but most scientists connect Mach only vaguely with definite scientific achievements or philosophical views, and not always correctly. His role as historian of science has been acknowledged and challenged. Least known is Mach's work as a teacher, work that has been taken for granted. I want to tell you about that part of Mach's work—in which he took an abiding interest—and bring it into the context of his general studies and ideas. My thesis is that Mach's thinking arose primarily from a need for didactic clarification and led him to search for the limits of man's intellectual capacity to understand himself and the world.

Mach's life

The external circumstances of Mach's life can be told in a few words. Biographical information is now readily available in English thanks to the recent book on *Mach Bands* by Floyd Ratliff[1]; there is also a modern German account of Mach's life by the late K. D. Heller,[2] of Haifa, which contains a cross section from Mach's writings. Mach was born on 18 Feb. 1838 in Turas, in the province of Moravia, then part of Austria, now Czechoslovakia—a province from which had come Amos Comenius, Gregor Mendel and Sigmund Freud. The Mach family moved into the neighborhood of Vienna when Ernst was a young child and spent many years in the country where educational facilities were scanty. Mach's education depended greatly on tutoring by his father, who had been a high-school teacher and whose ambition was to be a farmer.

Mach began his university studies in Vienna in 1856 and finished them in 1860. Shortly afterwards, in 1861, he became a university docent of physics. In 1864 he was appointed professor of mathematics and physics at the University of Graz, and in 1867 became professor of physics and director of the department of physics at the University of Prague. Mach lived in Prague for 28 years as a teacher, experimenter and scholar, active in university affairs. These were the most fruitful years of his life. Evidently he was not influenced by the mystique of the place and nothing in his writings reminds us of the Kafka-esque anguish and anxiety.

Frequent visits to Vienna helped to maintain contact with friends, in particular with the sociologist and writer Josef Popper. In 1895 Mach was called to Vienna to occupy a newly established chair of philosophy for "the History and Theory of the Inductive Sciences," mainly through the good offices of the classical scholar Theodor Gomperz, who was editor of the German translation of John Stuart Mill's *On Liberty* and who wanted to



ERNST MACH, 1838-1916. Drawing by Olga Pragor was completed four years before Mach's death. The portrait is from the Richard von Mises Collection in the Archives of the Center for History and Philosophy of Physics at the American Institute of Physics.

strengthen liberal ideas in the faculty. It was only for a few years that Mach had the opportunity to lecture on the history of science, because three years after his return to Vienna he suffered a stroke that paralyzed the right side of his body, fortunately without affecting his mental faculties.

When in 1901 it became impossible for him to fulfill his teaching obligations, he insisted on his retirement. Mach's successor till 1905 was Ludwig Boltzmann. Mach lived in Vienna till 1912; then he moved to the home of his son, Ludwig Mach, near Munich, where he died on 19 Feb. 1916. Ludwig Mach was a doctor of medicine, but he did not practice and was for many years his father's devoted assistant and after his death became the trustee of Ernst Mach's papers.

Ernst Mach had the normal career of the pre-1914 European university professor: a life spent near home, devoted to teaching and research with time for contemplation and recreation in the company of congenial friends. Mach experienced personal misfortunes, and a sense of the tragic nature of life was not unknown to him from the days of his youth. He had the satisfaction of seeing his views shared by a small group at home and abroad. In America, which he never visited, his writings became known through the efforts of Carl Carus and through publications in the magazines *The Monist* and *The Open Court*. His illness did not prevent him from reviewing and defending his thoughts but probably proved a serious handicap for a revision and expansion of his views in the light of scientific developments in the first decade of this century.

Physics in Vienna

I shall now turn to a discussion of Mach's years as a student and a young lecturer in Vienna and look at his intellectual development against the background of the academic locality and general scientific situation of this period.

Mach's physics professors were Andreas (Ritter) von Ettinghausen and August Kunzek. The former is known as the discoverer of a thermoelectric effect related to the Hall effect; he was director of the physics department and successor to Christian Doppler, who had occupied this chair for only two years. Ettinghausen was the first professor in a German university to introduce organized laboratory exercises and training in physical experimentation. Before, physics had been taught through demonstration experiments and required no more than a "kabinet," a room for the collection of demonstration apparatus for which Kunzek was responsible.

Josef Stefan was only a few years older than Mach and was a young lecturer when Mach was a student; he became the successor of Ettinghausen

in 1866. Josef Loschmidt, who began as a practical chemist and was much older than Stefan and Mach, became professor only in 1868 (to 1891) and lectured then—as one would expect—on molecular physics. Boltzmann was a student at Vienna between 1861 and 1865 and may have attended Mach's first lectures. The luminaries of the physical sciences faculty were the mathematician Josef Petzval, who also lectured on oscillations of elastic bodies and became famous for his design of the first achromatic double objective lens, and the astronomer Carl von Littrow (Littrow the younger; his father, Josef Johann, was the author of the popular astronomy book *Wonders of the Sky*).

Compared with the general situation of European physics at the time, the physics in Vienna in the fifties and sixties was not in the forefront of modern research, a position which it attained in the seventies through the triumvirate of Stefan, Loschmidt and Boltzmann. The principle of conservation of energy made its way only slowly into the teaching of the universities, and the thermodynamics and kinetic theory connected with the names Hermann Helmholtz and Rudolf Clausius had at Mach's time no representatives in Vienna. The same can be said about the electrodynamics of Wilhelm Weber and William Thomson (Lord Kelvin). Mach's great friend Josef Popper studied at the polytechnic in Prague between 1854 and 1857 and, as he tells in his memoirs,[3] heard about the energy-conservation principle for the first time in a physics lecture given in Vienna by Ernst Reitlinger in 1862, 20 years after Julius Robert Mayer's and James Prescott Joule's discoveries.

Interests and influences

It is therefore not at all astonishing that Mach, in his undergraduate years, was attracted to the work of two great personalities of the biomedical sciences in Vienna, the physiologists Ernst Brücke at the university, and Karl Ludwig at an affiliated medical academy and hospital. In modern jargon, that's "where the action was." Brücke was particularly interested in vision and speech, Ludwig in basic problems of physiology; Ludwig was the inventor of the kymograph for the recording of physiological phenomena. Both held leading positions, with Helmholtz, Emil DuBois-Reymond and Rudolf Virchow in the antivitalistic movement and attempted to make biology into biophysics, that is, into a causative life science. They used various physical methods in their physiological investigations and pointed to a new and wide field for the application of physics. Mach was impressed by this modern research activity, and his numerous publications on psychological and physiological problems between 1860 and 1875 indicate the strong influence of the physiologists of the Vienna school, which later provided the basic material for his scientific philosophy.

I want to mention here yet another possible influence on Mach, namely the great significance given in Mach's time to the pedagogical ideas of the philosopher and psychologist Johann Friedrich Herbart. Herbart, who at one time had held Kant's chair in Königsberg, shared Kant's belief in a strict separation of theoretical and practical, which means, moral philosophy. His writings on psychology as a science and on the possibility and necessity of applying mathematics to psychology had their effect on many scientists and admittedly also on Mach.[15] Herbart was later professor at Göttingen and never taught at Vienna—he died in 1841—but his views became widely known through the influence of the philosopher Franz Exner, who was, from 1848, an adviser to the minister of education and planner of the middle schools or gymnasiums in Austria where the main ideas of Herbart's psychology of education were to be realized. I believe that the general ideas of Herbartian didactics left their mark on Mach, especially the stress on organization and presentation of subject matter in accordance with the stores and processes of the learner's mind, that is, an economics of learning.[4]

The Viennese academic climate shows the background of Mach's early intellectual life. The totality of his philosophy or world view is, however, not entirely understandable from a knowledge of the academic influences only. One has to understand the political, social and religious atmosphere in Austria after 1848 with its struggle between clericalism, liberalism, nationalism and individualism. But it is probably true that the freedom of Mach's thought was nurtured in the enlightened atmosphere of his family and strengthened through the opinions of congenial friends and collaborators during the years of maturity. A closer investigation of all these factors in Mach's life is still missing.

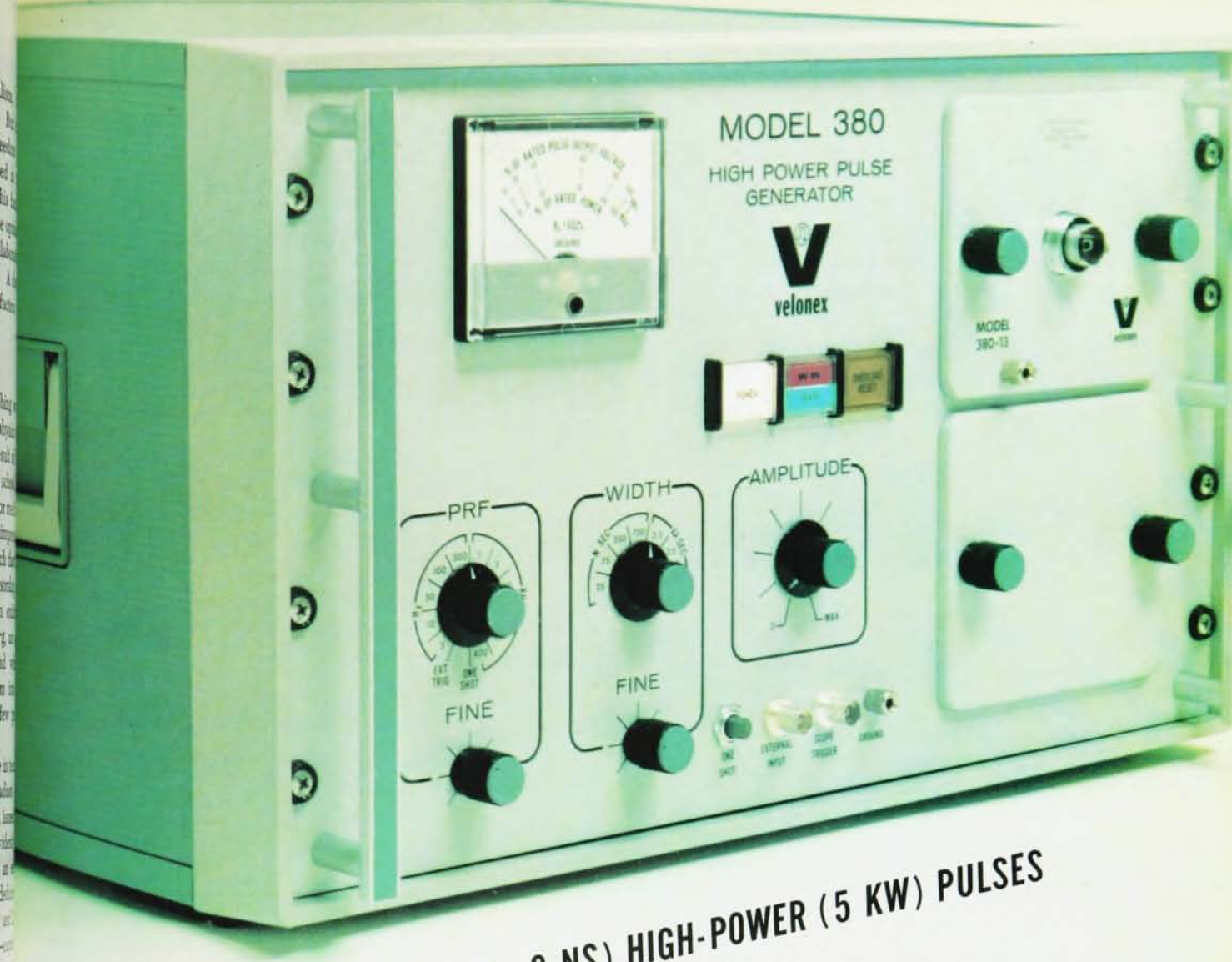
Docent in Vienna

Mach's first attempts in teaching were not in pure physics but in physics related to physiology. As a result of his affiliation with the medical school he offered a lecture in physics for medical students. In this course he impressed the clinical professors so much that he was nominated for a professorship in natural science at the then existing medical academy at Salzburg, an appointment he declined and which would have sidetracked him into a subordinate position, with few prospects for advancement.

After one year's experience in teaching he published *Compendium of Physics for Medical Students*, issued in 1863 in Vienna[5]; this was evidently a labor of love, intended as an educational message. Mach dedicated this book of about 270 pages and 225 illustrations to Ettinghausen—captatio benevolentiae, but there is no reference to support by an Austrian NSF or that this was a group project. In the preface he explains that the book should serve as a "leitfaden" or "guideline" to his lecture course, and that he had set himself the task "to acquaint his audience with the best accepted physical concepts in as short a time as possible." The last clause seems to be somewhat foreign to the tempo one usually connects with the city on the blue Danube, and one must accept it as a sign of Mach's extraordi-

---

The author graduated from Mach's university in Prague, has been on the faculties of the universities of Prague and British Columbia, and is now at Vanderbilt. His interests are in biophysics, physics teaching and history of science. He wrote, with J. D. Elder, *Principles and Applications of Physics*.



FAST-RISING (<9 NS) HIGH-POWER (5 KW) PULSES

- ☐ FOR NUCLEAR PULSE SIMULATION
- ☐ MICROWAVE DIODE DEVELOPMENT
- ☐ ULTRASONIC INVESTIGATIONS
- ☐ INJECTION LASER DRIVER
- ☐ GENERAL PURPOSE LABORATORY INSTRUMENT

Rapid rise time (<9 ns) invades the world of high-power pulses with Velonex's new Model 380. A model of versatility, Model 380 puts pulse powers to 5 KW at your command, gives you continuous variability of pulse widths from 25 ns to 25 μs and repetition rates from single shot to 400,000 pulses per second. It enables you, with accessory plug-ins, to vary rise and fall time to suit your needs, and step up output voltage to 1 KV, or output current to 100 amps.

You will find Model 380, with all its capabilities, easier to operate than most low-power pulse generators.

Write or phone today for details. Price $4,500.00

velonex
division of Pulse Engineering Inc.

560 Robert Avenue, Santa Clara,
California 95050 (408) 244-7370
TWX 910-338-0114

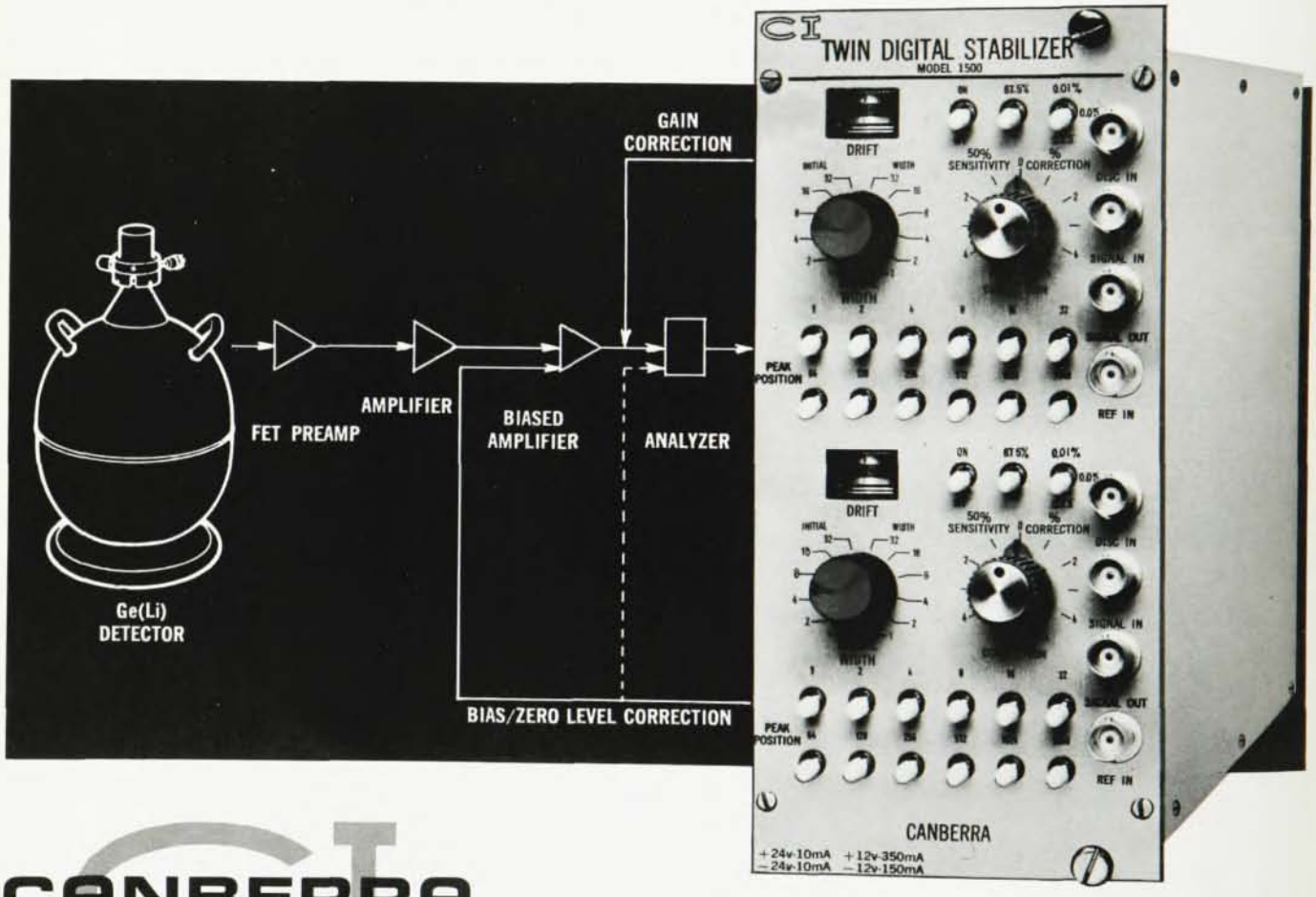
Are you getting the resolution from your Ge(Li) detector that you paid for?

High resolution gamma spectroscopy can now achieve resolutions approaching 0.25% at energies near 1 MeV, using cooled Ge(Li) detectors and high quality electronics. But, system gain and zero or bias level drifts can rob your system of nearly all its capability when accumulation periods exceed one hour.

The Canberra Model 1500 Twin Digital Stabilizer eliminates these drifts, totally, by a digital analysis and correction of the counts accumulating in your spectrum. Result? Instrumentation stability shortcomings, from preamp through analyzer (including post amplifier bias level drift), are compensated immediately, digitally, while your spectrum is accumulating. You get all of the resolution that your detector and electronics are capable of producing.

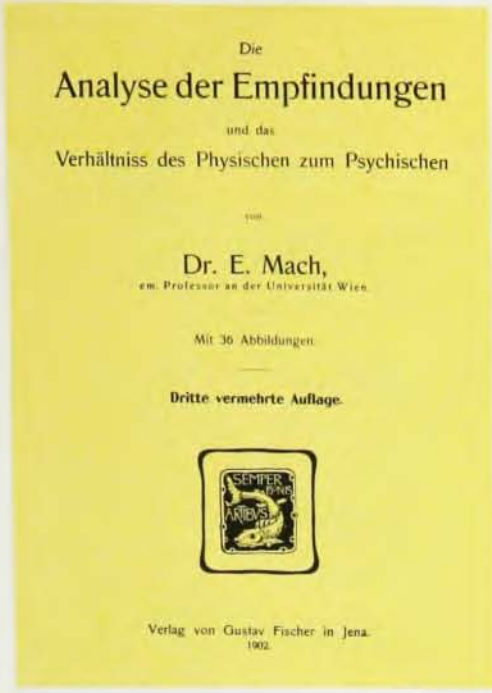
Write today for our brochure describing the Model 1500 and its applications. And begin getting all of the resolution your spectroscopy system is capable of producing.

The Model 1500 Twin Digital Stabilizer will ensure that you do!



CANBERRA

Canberra Industries, 50 Silver Street, Middletown, Conn. 06457



TITLE PAGES from two of Mach's books: *The Analysis of Sensations and the Relationship of the Physical to the Psychological*, and *Compendium of Physics for Students of Medicine.*

nary impatience; it somehow anticipates Mach's later emphasis on "economy" in science. He recognized quite clearly that "what makes the study of physics difficult for the student of medicine is not the ignorance of detail, but rather the unfamiliarity with the physical conceptual modes in general." He explains that there is a growing need for breaking down the compartmentalization of physics since "the now existing system is becoming, day by day, more impractical."

Ideas on atomistics

It is most interesting in view of Mach's later standpoint that he tried to develop a unitary theory of physics with the help of the atomistic theory, or as we would say now, the molecular theory, which he consequently applied to explain a variety of physiological phenomena. A considerable part of the book is devoted to discussions of blood circulation, the mechanics of the heart, ear and sound, the source of animal heat, heat economy of animals, light sensation and color, etc.

Regarding the atomistic hypothesis, the preface to the *Compendium* already sounds a warning, probably inserted after the course had been given and experience had been gained with this approach. Mach says here that atomism establishes nothing more than simple models and that the theory itself would need further explanation and is not "the last and the highest"; and further: "One can also consider the atomic theory as a formula that led to many results and in future may lead to more. In fact, whatever will be the future metaphysical view of matter, it should be possible to translate the results of the atomic theory into it, as one can express formulas in polar coördinates or in parallel coördinates." This is certainly a dualistic view of physical nature and must be regarded as one of Mach's many intuitions of things to come. A few years later Mach suggested that one could consider "molecular events musically," that is, as vibrating systems,[13] another aperçu in truly oracular formulation.

First textbook

Compared with the usual physics texts of the time, apart from the biophysical bias, Mach's *Compendium* is distinguished by its philosophical intention. It omits the detailed description of physical apparatus, or as Mach says in the preface, "of finely polished little hooks and screws," as they could be found in the elaborate woodcuts, for example, in Müller-Pouillet's general physics text, or in the similar French works of Jamin and Ganot, whence they found their way into many physics texts still in use at the beginning of this century.

The copy of the *Compendium* that I was privileged to use—lent to me by the Ernst-Mach-Institute—was Mach's own desk copy, and was evidently used by him for many years in Prague where the majority of his students in the main lecture course were first-year students of medicine. Into the book are bound blank pages on which Mach had made numerous remarks and bibliographical notes. That Mach did not attempt, however, to bring out a second edition would seem to indicate that his efforts had not been very rewarding. Apparently his medical students did not always appreciate his endeavors on their behalf. He was frequently questioned by medical students who wanted to hear from him "how much physics will a doctor need?" Mach's answer was, "A doctor always needs exactly as much physics as he knows. Knowledge one does not possess one cannot use." The German original version makes use of the double meaning of the word "brauchen" which is "to need" as well as "to use."

Professor in Prague

When lecturing in Prague, Mach developed other aspects of a physics teaching program. Mach was an experimental physicist, and many of his investigations in physcis and psychology show his talent in experimentation. Faced with the task of lecturing to large classes (probably no more than 100 students in the traditional experi-

mental course), he directed his attention to the development of demonstration experiments, particularly in mechanics and optics. The apparatus shown in the illustrations in his *Mechanics* were built by his shop assistant F. Hajek and formed in Prague a well kept "Mach Collection." Some of the apparatus was of original design, like the pendulum apparatus, the wave machine, the optical smoke box, and others. A list of Mach's lecture courses in Prague shows that he had not only held the main class in experimental physics every year, five hours a week, but offered from time to time special lecture courses on heat, light, physics teaching in high schools, etc. In Graz and Prague he also gave a number of public lectures that were later made available in print and were translated into English.[12]

YOUNG LECTURER. Mach's first attempts in teaching were not in pure physics but in physics related to physiology.

At this time Mach did not lecture specifically on the history of physics, but in his special lectures on heat, optics, electrostatics, etc., he probably treated the subject in an historical and critical manner, a method he later accepted in his three books on *Mechanics*[6] (1883), *Heat*[7] (1896) and *Optics*[8] (posthumously, 1921). These well known books, of which only *Mechanics* and *Optics* are available in English, are not really books of the history of these branches of physics but are specialized textbooks. For example, the German title of *Mechanics* reads literally, "The mechanics in its development," which does not give the same emphasis as "The development of mechanics," so that the English translator quite correctly rendered the title as *The Science of Mechanics* .... (The German "entwicklung" has been translated as "development," but it can also mean "elucidation," "deduction" and "derivation.")

The full titles of the two other books are *The Principles of Heat* and *The Principles of Physical Optics*, and they all have subtitles that stress that the treatment is historical and critical. Prima facie these are books on mechanics, heat and light, with a chronological approach and a strongly critical attitude. In the preface to the book on *Heat*[7] Mach wrote in 1896, "This book, just as the *Mechanics*, is on the one hand the result and on the other hand the basis of my lectures. Many a reader (that means teacher) must have had the experience that, relating generally accepted viewpoints with a certain enthusiasm, he suddenly recognizes that the matter no longer comes from the heart. Quiet considerations afterwards usually lead to the discovery of logical discrepancies that, once admitted, become unbearable." And later: "One should not expect in this work ... the results of archival research; the question is to find the *coherence* and the *growth of thoughts*, not to find interesting curiosities ... Where I speak about persons, they interest me only as intellectual and at the best as *ethical individualities*, ..."

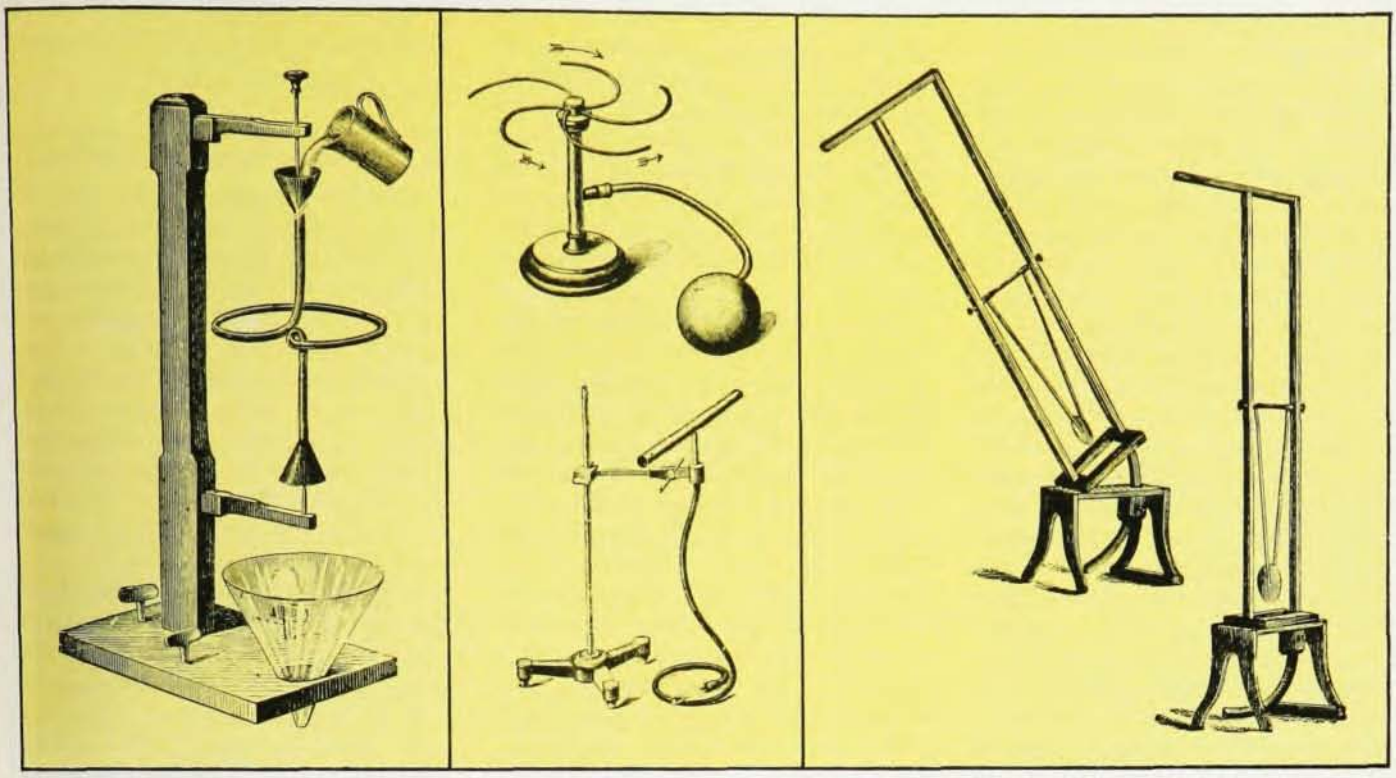
Critic of physics

Mach has been taken to task for not having been more careful in his historical research. If he failed in historiography because he may have ignored certain interpretations, we should not be too hard on him. Mach wanted to write not as a historian of science but as a critical physicist whose work arose from a didactic purpose. He did not write *Mechanics* to set the history of mechanics right but to set Newtonian mechanics right; not to discuss Newton's achievement in its historical meaning but in its scientific meaning. He tried to deduce for himself, his students and his readers the development of certain branches of physics along logical, not chronological, lines, and in spite of certain shortcomings these are still today, perhaps in the absence of something more perfect, considered useful and interesting for the student of the history of science.

In Vienna Mach, in his new professorship on the history and theory of the inductive sciences, found it possible to announce lectures on "The Development of Mechanics and of the Mechanical Sciences" and on "The History of the Science of Heat and Energy."[9] His first lectures on "Psychology and Logics of Research," of 1895–96, formed the basis for his last work, *Erkenntnis und Irrtum* (*Cognition and Error*), published first in 1905.[10]

Textbook writer

Out of his extensive classroom experience in Prague Mach also prepared, around 1890, a number of general physics texts intended for different levels of education: university or college physics and higher and lower physics for the middle schools (high schools). One of these books was intended for the use of Mach's students and to fulfill, as he says, a "local task."[11] An identical printing under a different title was to be used in the



DEMONSTRATION APPARATUS developed by Mach appears in *Mechanics*. Mach's shop assistant F. Hajek did the construction.

advanced grades of Austrian gymnasiums. Two physics texts for the higher schools of Germany were based on Mach's original, but adapted to the regulations in the schools of the German empire by two high-school teachers (1893–94), and went through several editions.

I will say at least a few words about Mach's educational intentions and quote a few lines that seem to have some significance for present educational debates. Mach was not an educator per se and he did not write at length on educational problems. In his physics textbooks he did not specifically try to advance his own ideas. However, the basic tenets of his philosophy, to which belong the rejection of dogmatism and speculation and appreciation for historical understanding and liberal interpretations, are expressed appropriately as they apply to education, for example, in the preface of the general-physics textbook[11] when he worte, "Concepts are not dogmatically introduced . . . but developed from facts. Theories and hypotheses come to discussion only when there is a need felt for them. Not through mentioning many dates and names, but through our genetic exposition does the historical moment gain its significance . . ."

Mach did not apply long-winded mathematical deductions, which, he believed, "did not contribute to understanding but make it more difficult to find an overall viewpoint." And in a lecture on the relative merits of education in the classics and the sciences[12] he also emphasized the importance of realistic and moderate aims in educational practice. "One point of importance here is that young students should not be exposed to premature abstractions but should be made acquainted with the subject matter . . . (and) the more general point of view is to be postponed . . . If our young men are not to enter the universities with blunted, impoverished minds, if they are not to lose their vital energies in the high schools . . . great changes will have to be made . . . (Otherwise) they leave as poor creatures who have learned too much . . . (and) what they have acquired is a spider's web of thoughts too weak to furnish sure supports but complicated enough to produce confusion."

In his autobiographic references Mach did not particularly mention his interest in education, probably because teaching belonged to his everyday work. That he felt he was a teacher and expected to appear to others as such follows from a story he tells in a footnote in the *Analysis*.[15] Stepping into a bus in a tired state of mind he sees a man enter from the other side whom he identifies as an "old, shabby schoolmaster," when he recognizes that he is seeing himself in a big mirror. As he explained, "The class habitus was to me more familiar then my own special habitus."

Descriptive laws of science

Essential ideas of Mach developed and were brought to fruition during his various teaching activities. One of his most important writings—and one that is least known (it is not included in George Sarton's *Horus*)—is a small book, the first literary fruit of his activity in Prague, which carries the rather longish title *History and Root of the Principle of Conservation of Energy*."[13] Published in Prague in 1872 and again in Leipzig in 1909, it was translated into English in 1911. Mach stressed in his later writings that this little book contained many of his thoughts on the methods and aims of science, and indeed much of what he wrote later was in many ways a commentary on the thoughts ex-

pressed in this modest volume.

As the title indicates, Mach set himself the task of exploring the origin of the idea of conservation of physical energy. Both term and concept were relatively new, as I mentioned before, but by 1872 had become more or less accepted and Mach now attempted to show historically "that this theory is by no means as new as one tends to believe," and philosophically "that this theorem by no means stands and falls with the *mechanical* view of the world [and that] its logical root is deeper in our minds than that view." The book also contained the reprint of an earlier paper by Mach, dealing with the definition of mass, which he had unsuccessfully attempted to publish in *Annalen der Physik* and which he had therefore placed in 1868 in a less known journal, *Carl's Repertorium für physikalische Technik*, and which he now included in his book on energy to bring its contents to the attention of the wider scientific community.

In this paper Mach had already proposed the idea that the laws of physics are descriptions and should not be conceived as causal relationships, anticipating Kirchhoff by two years. The most we can say about phenomena is that they depend on each other or that there exists a functional relationship between quantities we can determine. Laws of science, Mach defined, are limitations to our expectations under the guidance of our experience; thus the law has restrictive character since any increase in scientific knowledge leads to a restriction of expectations. These expectations are the product of a psychological desire to orient ourselves in nature.

Scientific economy

In the general discussion of the meaning of laws in science Mach formulates in this book another major thought, a corollary, namely the principle of scientific economy. With increasing accumulation of knowledge, scientists are motivated to obtain a reduction in intellectual effort and to achieve an economy in the structure of their laws. This principle has some resemblance with the lex parsimoniae or "Occam's razor" and with Newton's rules of scientific thinking, but for Mach the economy of thinking is conceived as an essential of our particular form of civilization. He had formed the idea in Graz under the influence of a colleague, Emanuel Hermann, professor of national economy, whom he quotes as having said that "science also has a problem of economy or thrift." In his book on *Heat*[7] Mach discusses the economy principle also in connection with the Carnot coefficient of heat engines.

In one of the later editions of *Mechanics* Mach reminisces that the idea of an economy of thought developed in him greatly through the experience of teaching and that, as a young lecturer, he flattered himself to have been the sole possessor of this truth. In the book on energy he also said "that in the sciences . . . we are chiefly concerned with the convenience and saving of thought I have maintained since the beginning of my career as a teacher." He again stressed the didactic connection when he wrote,[12] "The aim of instruction is simply saving experience; the labor of one man is made to take the place of that of another." But economy in teaching and in research is for him a method, not a doctrine of purpose. In the book on heat he wrote, "The methods through which knowledge is acquired are of an economic nature. What kind of use will be made of the acquired knowledge . . . has nothing to do with scientific methods." Mach has been accused of regarding the economy of thinking as the *aim* of science, and on the basis of such misunderstanding a great physicist risked the gibe that Mach's economy principle would demand the suspension of all science, because "if we want to economize, the best way would be to stop thinking entirely."[14]

We are, in fact, approaching this ideal in our modern civilization with computers, and with their help we may one day be able to abandon the formulation of laws—just store all our machine-recorded observations and, when needed, extract the specific information from the memory tapes. And the economy of thrift of Mach's period, with its principle of a balanced budget, has now been replaced by the Keynesian modern economy of planned credit, and we do not only take scientific evidence on credit or faith, but are prepared to risk large expenditures of public finances on the outcome of scientific predictions, a procedure unheard of in Mach's time.

One science

Mach was, of course, aware that scientists did not only attempt to make and accumulate observations; they want to create unifying, objective theories. Such theories, he noted, unavoidably establish a wall between the physico-physiological and psychological sciences if they take recourse to such metaphysical concepts as "matter" and "soul" or to such speculative constructs as "atoms" and "faculties." Mach's interest in physics, physiology and psychology made it desirable for him to look for a common standpoint that would allow him to maintain it unchanged when turning from one field to the other. He believed to have discovered this common approach in his *Analysis of Sensations*,[15] a book first published in 1885, two years after *Mechanics*. The subtitle "The relationship between the physical and the psychological" indicates that he tried to bridge the "communication gap" between physics and psychology through a consequent phenomenological fixed point and the introduction of "elements" of experience or sense impressions. The interpretation of the term cannot be our task here, but it should be mentioned that its expansion in neopositivistic philosophy led to the replacement of the elements by "protocol sentences."

Mach did not deny the value of independently existing special sciences. He was satisfied with having proposed an encyclopedic union that would shield the sciences from particular, superfluous concepts. The unity-of-science movement of the scientistic Vienna Circle, who used to claim Mach as one of their own, far exceeded Mach's intentions. When Mach expressed himself against metaphysical assumptions, he did not mean to "explain away an objective world in terms of subjective ideas," as J. D. Bernal wants us to believe,[16] nor was he aware that thereby his philosophy "played a role in the service of the bourgeoisie."[17] His rejection of metaphysics was not for lack of imagination or inability to invent "constructs" or appreciate models and symbols. In the arguments with Boltzmann on atomistics he did not object

to a discontinuous-space concept as such but only to the crude mechanistic picture of the atomists of 1899.[7]

Extrascientific motivations

I believe that Mach's rejection of metaphysics is prior to his demand for a purely analytic conception of science and is based on experiences that convinced him that man's mind is incapable of reaching further than the manipulation of elements of sensations. To borrow a term from the *Analysis* of Mach's famous compatriot, it seems that he tacitly expected a "censor" to act in the human mind who would restrict man's intellectual aspirations, as in Sigmund Freud's theory it limits his instinctive aspirations. In the field of speculation Mach wished man to be passive and in this way achieve a perfect, man-oriented science for imperfect mankind.

Not unlike Michael Faraday (and Pierre Duhem) he kept the door between the science laboratory and the church shut, but Mach barred the door of the laboratory from within to protect science from the exuberance of human fantasy and emotionalism of any kind.[10] Mach considered religious faith to be everybody's private affair and he rejected any "concordat" between science and religion and the cosmic religiosity supported by Planck. His upbringing in a liberal and humane atmosphere saved him from the conflict of conscience that vexed many others of his generation, as for example Ernest Renan, and Mach did not feel at any time the need for an "examen de conscience," as Renan did.

Mach was never explicit about the motivations of his ideas and did not leave us with a summa of his beliefs or a philosophical testament. Evidently there was no inclination in his disposition for scientific lyricism or pomposity that easily go hand in hand with the creation of a synthetic philosophy and even of a positivistic system. By his own admission he liked to ramble through science, and he also presented his thoughts preferably analytically in the form of short articles rather than through a deductive, comprehensive tome. With the exception of *Mechanics* his books are collections of more or less independent essays on a variety of related topics. Occasionally he may have felt the lack of power of synthesis or of his inability to subscribe to a definite doctrine, but as he wrote in *Mechanics* he preferred "to endure an incomplete world view rather than to find satisfaction in a seemingly complete, but inadequate system."

Enlightened teacher

Having recognized the wide range of Mach's interests we find it obvious that Mach was neither a specialist's specialist nor a generalist in the current sense. He originated several fields of research but without exhausting their potentialities, and he also extracted from his specialized studies general principles of new insight without claiming for them more than a relative validity for the "human condition." He attempted to spread the essence of his thoughts—which he refused to call a "philosophy"—through the spoken and the written word, but he never became dogmatic. His intuitive power of foresight led him to recognize future developments in the sciences. His inspirations were reactions rather than actions—reactions both to

Ernst Mach Chronology

1838	Born 18 Feb., in Turas, Moravia
1856–60	Studied at Vienna University; Dr phil
1861	Privatdocent of Physics, Vienna University
1864	Professor of Mathematics and Physics, Graz University
1867	Professor of Physics, Prague University Married Louise Marussig (4 sons, 1 daughter)
1872–73	Dean of the Philosophical Faculty
1879–80	Rector of the (undivided) University of Prague
1883–84	First Rector of the German University of Prague
1895	Professor of Philosophy, particularly for the History and Theory of the Inductive Sciences, Vienna University
1896	Title of 'Hofrat' (Court Councillor); Secretary of the Mathematical-Scientific Division of the Imperial Academy of Vienna
1898	Suffered paralytic stroke
1900	Retired 1 May
1901	Appointed Member of the Upper Chamber of the Austrian Parliament
1912	Moved with his wife to the home of his son, Ludwig Mach, in Vaterstetten, Bavaria
1916	Died 19 Feb., in Vaterstetten

Periods of Research Activities

1860–65	Optical and acoustical investigations
1860–80	Psychological work on perceptions
1872–1910	Historical and epistemological studies
1878–89	Experiments on projectile motion

(Research publications by Mach and his students number about 140)

Book Publications (first editions)

(Titles literally translated from the German)

1863	Compendium of Physics for Students of Medicine
1872	History and Root of the Principle of the Conservation of Work
1883	The Mechanics in its Development, Rendered Historically and Critically
1885	The Analysis of Sensations, and the Relationship of the Physical to the Psychological
1890	Various general physics texts
1896	The Principles of the Science of Heat: Historically and Critically Rendered
1905	Cognition and Error
1921	Principles of Physical Optics: Developed Historically and Epistemologically-Psychologically

his reading in the history of physics and to classroom situations. He looked back to find the mistakes of the scientific past rather than to develop his divinations into what he probably felt would be the mistakes of the future.

As historian of science he was not interested in teaching the development of science as part of a glorious and, as it now is often taught, a vainglorious "Western tradition." Basically he was more interested in the questions that could be asked than in the answers that could be given now. The fundamental trait of his attitude was that of the enlightened teacher, of a man who shows others how to observe and to give meaning to their observations within self-imposed bounds, with the good teacher's understanding of the intellectual limitations of man's capacities.

Humane personality

Mach's papers and books, because of their discursive nature, are still capable of speaking to us with a new resonance of meaning. "Reading Mach's works," Albert Einstein wrote, "one feels the delight which the author had in the composition of his clear, concise sentences. However, not only the intellectual enjoyment and the appreciation of the easy style make the reading of his books so attractive, but equally the kind, humane and hopeful convictions that shimmer between the lines when he is talking about what concerns mankind."[18] His position as a critic of scientific civilization is never marred by skepticism though he sometimes shows a guileless irony. His only weakness is the tendency to repetition, probably in agreement with his didactic advice to teachers—according to a Prague tradition—in which he quoted from *Faust*, Part 1: "Thrice must the words be spoken." He wrote for a public of scientists, avoiding in his style a verbosity that would more ingratiate than educate. He did not feign hypotheses and did not feign culture. With no obligation to a scientific "estate" or to the public at large, he appears to us as the last liberal in the academic world who cherished freedom of thought much more than the safety, and bondage, of intellectual tenure.

I believe that much of the strength to go it alone came to Mach from his devotion to education. It was this constant human and social interest that gave motivation to the whole of his activity. It explains also the understanding—which he shared with his friend Popper—that one should place modest expectations on the intellectual as well as on the moral integrity of the individual man but expect everything from the establishment of workable and just institutions, science being one. Matthew Arnold observed about a hundred years ago that "while the leading humanists have brought their minds and energy to bear upon the teaching of their own studies, the leaders in the natural sciences, the Davys and Faradays, have not."[19] Arnold describes a situation that is still very much with us today, in which the university scientists are expected to treat teaching just casually. Mach was not the only exception to the rule. But he was an outstanding example of a scientist and teacher who gave equal weight to the two components of a science professor's daily tasks.

I don't think that Mach's strong commitment to teaching and education could find many imitators today. Mach was too singular a personality and his activity too much bound to the conditions of his time to become an acceptable model in our time. The totality of his work, his experiments, his historical interests, his philosophical ideas and his humane personality, however, will long be remembered. And, as I hope I have shown, through a recognition of Mach's central concern for education we can best appreciate the full scope of his thoughts and the origin of his many inspired reflections.

* * *

This paper is a shortened version of an article to be published next fall by Harvard University Press in the Proceedings of the Mach Symposium, *Raymond J. Seeger, editor. Information on Mach's teaching activity at Prague has been collected for me by my old friend Julius Kroczek, to whom I express my thanks. I also gratefully acknowledge the assistance of F. Kavka, director of the Institute for the History of Charles University, Prague.*

References

1. F. Ratliff, *Mach Bands, Quantitative Studies on Neural Networks in the Retina*, Holden-Day, San Francisco (1965).
2. K. D. Heller, *Ernst Mach, Wegbereiter der modernen Physik*, Springer-Verlag, Berlin (1964).
3. J. Popper-Lynkeus, p. 26 in *Mein Leben und Wirken, Eine Selbstdarstellung*, Carl Reissner (1924).
4. J. F. Herbart, *The Science of Education* (translation by H. M. Felkin, E. Felkin), D. C. Heath, Boston (1896).
5. E. Mach, *Compendium der Physik für Mediziner*, Wilhelm Braumüller (1863).
6. E. Mach, *The Science of Mechanics: A Critical and Historical Account of Its Development* (translation by T. J. McCormack, new introduction by K. Menger), Open Court, LaSalle, Ill. (1960).
7. E. Mach, p. 431 in *Die Prinzipien der Wärmelehre. Historich-kritisch dargestellt* (4th ed.), J. A. Barth, Leipzig (1923).
8. E. Mach, *The Principles of Physical Optics: An Historical and Philosophical Treatment* (translation by J. S. Anderson, A. F. A. Young), Dover, New York (1953).
9. J. Mayerhöfer, "Ernst Mach as a Professor of the History of Science," p. 337 in *Proc. 10th Internat. Congress of History of Science, Ithaca*, Vol. 2, Hermann, Paris (1962).
10. E. Mach, *Erkenntnis und Irrtum* (5th ed.), J. A. Barth, Leipzig (1926).
11. E. Mach, *Leitfaden der Physik für Studierende* (2nd ed.), Tempsky (1891); *Grundriss der Naturlehre*, Tempsky (1891).
12. E. Mach, p. 285 in *Popular Lectures* (translated by T. J. McCormack) Open Court, La Salle, Ill. (1895).
13. E. Mach, p. 51 in *History and Root of the Principle of the Conservation of Energy* (translated and annotated by P. E. B. Jourdain), Open Court, La Salle, Ill. (1911).
14. M. Born, p. 207 in *Natural Philosophy of Cause and Chance*, Dover, New York (1948).
15. E. Mach, p. 299 in *Die Analyse der Emfindungen und das Verhältnis des Physichen zum Psychischen*, Gustav Fischer, Jena (1918). (English translation by Dover, New York, 1959).
16. J. D. Bernal, p. 528 in *Science in History*, Watts (1954).
17. "Mach," p. 527 in *Meyers Neues Lexikon*, Vol. 5, VEB Bibliog. Inst., Leipzig (1964).
18. A. Einstein, "Ernst Mach," in Physikal. Zeitschr. **17**, 104 (1916).
19. M. Arnold, p. 261 in *Schools and Universities on the Continent*, Macmillan, New York (1868). □