MACH AND ATOMISM*

The place of Ernst Mach (1838–1916) in the history and philosophy of science is ambiguous. As a critic of Newtonian views on space and time, he played an important role in preparing the way for Einstein's theory of relativity; and his views on scientific method and the interpretation of physical theories make him an influential ancestor of modern logical positivism. Yet his persistent opposition to atomic theories, and his ultimate refusal to accept relativity, raise the suspicion that Mach's viewpoint provides a basis only for destructive criticism, and tends to discourage the development of hypotheses that may turn out to be fruitful.

Professor Rosenfeld offered the following judgment on Mach's position about 10 years ago:

When Mach criticized the atomic theory he of course bet on the wrong horse and he has to bear the blame for it. But apart from that his paper on the Erhaltung der Arbeit was just a very sound warning against the danger of introducing arbitrary elements into atomic theory. His whole point was that one has no right to introduce and to apply to atoms the mechanical concepts which have been derived from experiences about macroscopic bodies, unless one has cogent experimental reasons for doing so. I therefore think it is unfair to criticize Mach just because he happened to draw the wrong conclusion, as his criticisms were completely sound.¹

On the other hand, one cannot ignore the comment of Einstein about Ostwald and Mach:

the prejudices of these scientists against atomic theory can be undoubtedly attributed to their positivistic philosophical views. This is an interesting example of how philosophical prejudices hinder a correct interpretation of facts even by scientists with bold thinking and subtle intuition.²

Max Planck, earlier in the century, felt it necessary to combat the influence of Mach's views on the younger generation of physicists (just as Lenin felt it necessary to rescue his fellow-Marxists from Machist corruption³). Lecturing at Leiden in 1909, Planck asserted that Mach's viewpoint, which denied reality to anything but human sensations, tended

to divert the attention of scientists from the true goal of scientific endeav-our, which was to establish the nature of the external world independent of the human observer. Judged by the fruits of his method, Mach was a false prophet. Again, at a lecture in Berlin in 1913, Planck attacked the anti-atomist position:

Whoever rejects faith in the reality of atoms and electrons, or the electromagnetic nature of light-waves, or the identity of heat and motion, can never be found guilty of a logical or empirical contradiction, but he will find it difficult from his standpoint to advance physical knowledge.5

If we are to judge a scientific method or philosophy such as Mach’s by its ‘results’, we must be much more careful than heretofore in describing what those results actually were. In particular, we cannot be content to say that Mach was simply ‘right’ or ‘wrong’ on a certain point, judged by accepted modern views. Instead, we must examine physical theories as they stood in the late 19th century when Mach was criticizing them, and see what he actually said about them. When Mach’s statements on atomic theory are put into their historical context, it turns out that Mach’s position is much more complex than is generally reported. Moreover, some of the scientific questions discussed by Mach are by no means settled even today, to say nothing of the philosophical or methodological ones. Thus, while we maintain that the philosophy of science cannot usefully be studied apart from the history of science, we find that history by itself cannot be used to justify the exclusive validity of any one scientific method.

I. THE BACKGROUND FOR MACH’S OPINIONS ON ATOMISM

I shall summarize here the various theories and schools in the late 19th century which were concerned with atomism in one way or another, making only those distinctions that seem necessary in order to understand where Mach placed himself:

(1) the Atmospheric Atom Model of the late 18th and early 19th centuries. As the model was usually described, there are two kinds of atoms: matter-atoms and ether-atoms. Matter-atoms attract each other, the attractive force being inversely as the square of the distance, at least at large distances; ether-atoms repel each other, and matter-atoms attract ether-atoms.6 Each matter-atom is therefore surrounded by an atmosphere of ether-atoms. Other atmospheres, composed of caloric for example, may
be added. The model provides the basis for explaining electrical, magnetic, thermal, mechanical, and gravitational properties by postulating imponderable particulate fluids. This model, with various modifications, can be found in most physics textbooks published between 1780 and 1860; of particular interest to us is Anfangsgründe der Physik (Wien 1844; 4th ed. 1860) by Andreas Ritter von Ettingshausen, one of Mach's teachers at Vienna.

(2) Dynamism, the belief that the ultimate basis for the properties of matter is to be found in forces acting through space. Boscovich had shown how the atom could be reduced to a point-center of force, and Kant had advocated the construction of a system of physics based on attractive and repulsive forces. This suggestion of Kant had been taken up by the German school of Naturphilosophie, and, according to some historians of science, exerted considerable influence on the development of electromagnetism (Oersted and Faraday) and the discovery of the Law of Conservation of Energy. In the 19th century, Dynamism split into two distinct theories:

(2a) Physical Dynamism became a respectable part of physics, as another version of atomism; it was usually treated as a hypothesis subject to modification in the light of experimental discoveries, and used by such scientists as Hamilton, Helmholtz, Maxwell, Lord Kelvin, Van der Waals, and Sutherland. Maxwell and Kelvin emphasized the artificial nature of the assumption that atoms exerted forces on each other proportional to some inverse power of their distance, and, but for the mathematical difficulties involved, would really have preferred something like the vortex theory of the atom, which involved nothing but matter and motion with no need for postulating occult 'action at a distance' forces. Boltzmann, in the 1890's, tried to divert criticism of atomic theory against this one version of it, so as to leave unimpaired the atomic concept itself. In the 20th century the model of atoms or molecules exerting a combination of attractive and repulsive forces on each other has been used extensively (by Lennard-Jones and many others) though it is no longer taken as a fundamental model, but rather one that can be derived as an approximation from quantum theory.

(2b) Philosophical Dynamism, in the non-mathematical form used by the Naturphilosophen, developed into anti-atomism by accepting the reasoning that if all the properties of matter depend only on the forces
exerted by atoms, then the atom itself is superfluous. This view was main-
tained by Immanual Hermann von Fichte (son of the better-known phi-
losopher Johann Gottlieb Fichte), who attacked atomism – both the
Atmospheric Atom Model and Physical Dynamism – in a series of
articles starting in 1854.\textsuperscript{11} Gustav Fechner (soon to be the founder of
psychophysics) defended atomism\textsuperscript{12}, though most physicists paid no at-
tention to Fichte. The views of both sides in the Fichte-Fechner debate
were already becoming obsolete, and Ernst Mach was one of the few
working scientists who had any interest in this controversy.

(3) The \textit{Kinetic Theory of Gases}, revived in the 1850's by Joule, Krönig,
and Clausius, and further developed and applied by Maxwell, O. E. Meyer,
Van der Waals, and (in Vienna) Stefan and Boltzmann.\textsuperscript{13} It may be re-
garded as the leading example of a mechanistic physical theory; it claimed
to reduce the observable macroscopic properties of gases to the motions
and collisions of atoms, calculated according to the principles of Newton-
ian mechanics. The strength of the Kinetic Theory was its success in ex-
plaining and predicting transport properties such as viscosity and dif-
fusion; its weakness was the failure to account for specific heat capacities
of polyatomic gases. While the Kinetic Theory was based directly on an
atomic hypothesis, it did not rely directly on a detailed atomic theory such
as the Atmospheric Atom Model or Physical Dynamism. Instead, it re-
quired little more information about atoms than their sizes, and con-
versely it greatly strengthened belief in the reality of atoms by providing
the first reliable estimates of atomic dimensions.

(4) \textit{Chemical Atomic Theory}, based on Cannizarro’s revival of Dalton’s
theory in 1860. This theory was concerned mainly with the atomic consti-
tution of molecules, the interpretation of chemical reactions, and the de-
termination of relative atomic weights. The conclusions of Chemical
Atomic Theory, unlike those of Kinetic Theory, were independent of the
absolute sizes and weights of the atoms, and anti-atomists therefore tried
to reformulate these conclusions in terms of relative combining weights
without reference to atoms.\textsuperscript{14}

(5) \textit{Physical Atomism}, the common ground of all scientists who believed
in the reality of atoms, and/or their usefulness in constructing scientific
theories. Physical Atomism was no longer a single coherent theory after
about 1850, since different models had to be used to explain different
properties of matter. Although Physical Atomism was highly vulnerable
to criticism for this reason, it was those theorists who did not retreat into phenomenology but continued to explore, unsuccessfully, all the possible atomic models consistent with classical physics, who must be given a large share of the credit for the downfall of classical physics. In saying this we are in effect shifting the burden of proof from those who want “to apply to atoms the mechanical concepts which have been derived from experiments about macroscopic bodies” (Mach's view as stated above by Rosenfeld) to those who wish to deny that the realm of the invisible can be interpreted with the help of the same laws that apply to the realm of the visible. In other words, we consider the oft-ridiculed preoccupation with mechanical models in 19th-century physics as a perfectly reasonable attempt to push a successful technique as far as possible.

(6) The tradition of Pure Thermodynamics, uncontaminated by atomism. Many scientists thought it worthwhile to preserve Thermodynamics as a set of laws based directly on experiment, whose validity would not depend on the acceptance of any theory about the internal structure of matter. Note that these scientists – Clausius, Kelvin, Rankine, Helmholtz, Gibbs, and Max Born – were not anti-atomists. They all contributed to atomic theory in separate publications.

(7) Attempts to find Mechanical Analogies for Thermodynamics (Hamilton's Principle, principle of least action, etc.). Only a few physicists – Clausius, Szily, Boltzmann, and Helmholtz – did any serious work along this line, but the subject aroused enough interest for the British Association to request a special report on it.15

(8) Attempts to establish a Statistical Interpretation of the Second Law of Thermodynamics. Maxwell, who ridiculed the German attempts to find mechanical analogies for the Second Law16, maintained that the Second Law is essentially statistical in nature, and proposed the celebrated ‘Maxwell Demon’ to illustrate this thesis.17 Boltzmann put the statistical interpretation on a more quantitative basis with his H theorem, and the subject was later discussed at length by Kelvin, Tait, Jeans, and Paul and Tatiana Ehrenfest.18 Gibbs and Tolman emphasized the view that the statistical aspect of irreversibility (ordered motions becoming disordered) stems more from the limitations of human observations of phenomena than from the nature of the phenomena themselves.19 It should be noted that such statistical interpretations, though often presented in conjunction with the Kinetic Theory of Gases, are not a logical consequence of that
theory; one can accept the results of Kinetic Theory without committing himself to a fundamental explanation of irreversibility. The reversibility and recurrence paradoxes, popularized by the Ehrenfests, were used by the anti-atomists to attack not only the Statistical Interpretation of the Second Law but also the Kinetic Theory and Physical Atomism in general. Atomism was said to be defective because a system of atoms governed by Newtonian mechanics could not exhibit the irreversible behaviour which is a fact of experience.

(9) Energetics, a generalization of thermodynamics which claimed to provide a unified phenomenological description of all physical phenomena. The proponents of Energetics—Ostwald, Duhem, Helm, and others—were active anti-atomists. The name ‘Energetics’ came from an earlier paper of Rankine, who in fact does not belong to this school at all but rather to Pure Thermodynamics and Physical Atomism. It is important to observe the distinction between Pure Thermodynamics—which claims validity only within a limited region and is mainly concerned with axiomatizing results already known, while conceding the usefulness of atomism in finding new results—and Energetics, which claims to be the only legitimate scientific theory, sufficient unto itself.

(10) Empiriocriticism, a critical view toward all scientific hypotheses not directly induced from experiment. The term was originally associated with the work of Avenarius, but since the publication of Lenin’s book it has been applied to Mach, Stallo, Pearson, and others who hold similar views. Empiriocriticism claims to stand above all theories (1)–(9), being more concerned with the method than the content of science. The detailed criticism of Kinetic Theory and Physical Atomism by Stallo presumably was consonant with the views of other members of the group; Mach, in particular, praised Stallo’s book, and dedicated the second edition of his own treatise on heat to Stallo.

Let us now see how Mach traced his own path through this maze of positions, starting from the first one and ending up at the last one, without ever completely accepting any of the intermediate ones.

II. MACH’S EARLY PRO-ATOMISM (1862)

At the age of 24, Mach wrote a *Compendium der Physik für Mediciner*, which he dedicated to “seinem hochverehrten Lehrer, Herrn Andreas
Ritter von Ettingshausen ... aus Hochachtung und Dankbarkeit". In this rare and seldom-cited work, Mach wrote that it is no longer possible to treat such phenomena as heat and light separately in a textbook of physics; they should rather be discussed systematically as various kinds of molecular processes which happen to give rise to light, heat, or sound. "Indeed, the customary division is not physical but rather physiological".

He uses the atomic theory in this book, not because it is the most recent and advanced, and requires no further support, but rather because it brings together the phenomena in a simple and perspicuous [anschaulich] connection. One can, if he wishes so to express himself, consider that the atomic theory is a formula that has already led to many results, and will lead to many others. In fact, whatever may be the metaphysical view of matter in the future, one can always transcribe into this view the results obtained by atomic theory, just as one can express formulae by polar or rectangular coordinates.

"The goal of physics", says Mach in this Compendium, "is to extract a small number of principles from the phenomena. Since these ultimate principles frequently have not yet been found, we must be content with a hypothesis, the so-called atomistic theory." Citing Fechner's Atomenlehre, he says that we have to choose between the Dynamic and Atomic theories; in other words, does matter fill space continuously, or should we imagine that there are empty places between the occupied parts of space?

According to the atomistic theory one attributes the essential properties of matter to particles or atoms, separated by empty space; one assumes that they are impenetrable and inert, and moreover that they can interact with each other by means of any kind of force. ... The atomic theory agrees with physical phenomena much better than the dynamic theory, yet frequently it is subjected to critical examination.

Mach then quotes nearly a page of pro-atomistic arguments from Fechner's book.

"Certain physical phenomena can only be explained by the atomistic theory", according to the young Mach. "First is the polarization of light. Light depends on aether-vibrations...." "In favor of the atomic theory is the fact that it explains all physical phenomena from a single viewpoint. Under certain assumptions about the nature of the forces acting on the atoms, it is possible to reduce all phenomena, at least in the most general features, to the equilibrium and motion of atoms." Then follows an
exposition of the Atmospheric Atom Model which we have described above.

Mach also gives a qualitative exposition of the Kinetic Theory of Gases\textsuperscript{27}, citing the papers of Kronig and Clausius, and discusses the relation between the spectra of gases and molecular structure.\textsuperscript{28} In a paper ‘Molecular Forces in Fluids’, published in 1862 when he had just finished writing his \textit{Compendium}, he indicates that he has also applied the Kinetic Theory to capillary phenomena.\textsuperscript{29}

There are three obvious sources for Mach’s atomic theory: first, Fechner’s \textit{Atomenlehre}; second, the papers of Kronig and Clausius on Kinetic Theory; and third, Ettingshausen’s textbook \textit{Anfangsgründe der Physik}, which he does not cite but was presumably quite familiar with. These and other sources exposed him to four of the theories listed above, and three of them he accepted: the Atmospheric Atom Model, the Kinetic Theory of Gases, and Physical Atomism. We know that he was aware of the existence of the other one, Dynamism; since Fechner cited his own articles in the \textit{Zeitschrift für Philosophie} replying to Fichte’s criticisms of atomic theory, it is reasonable to suppose that Mach also read Fichte’s articles.

Fichte’s attack on atomism provides an interesting sidelight on 19th-century philosophy of science which I hope to discuss in more detail elsewhere. Here I must merely note its significance in the development of Mach’s views: Fichte proposed an anti-atomic position which Mach explicitly rejected early in his career, and did not return to even when he himself turned against atomism. The notion that matter is space-filling force was no more attractive to Mach than the notion that matter is composed of discrete particles; both went beyond the limits of sense-experience and therefore could not have any scientific foundation.

A more detailed analysis of Mach’s early views on atomism may be found in a paper contributed by Professor Erwin Hiebert to the Mach Symposium held in Washington, D.C., December 1966, to be published by Harvard University Press.

\section*{III. MACH TURNS AGAINST ATOMISM (1872)}

According to Mach’s own account\textsuperscript{30}, it was the composition of his \textit{Compendium} that “first made me conscious of the insufficiency of [the atomic]
theory”. In his lectures on psychophysics in 1863, “I already stated clearly that we are not justified in thinking of atoms spatially.” “My attempts to explain mechanically the spectra of the chemical elements and the divergence of the theory with experience strengthened my view that we must not represent to ourselves the chemical elements in a space of three dimensions. I did not venture, however, to speak of this candidly before orthodox physicists.”

Mach’s first outright public rejection of atomism came in his monograph on the history of the principle of conservation of energy, published in 1872. He observed that the conclusion that, if heat can be transformed into mechanical work, it must consist in mechanical processes – in motion – has spread over the whole cultivated world like wildfire ... now people are everywhere eagerly bent on explaining heat by means of motions; they determine the velocities, the average distances, and the paths of molecules, and there is hardly a single problem which could not, people say, be completely solved in this way by means of sufficiently long calculations and of different hypotheses. No wonder that in all this clamour the voice of one of the most eminent, that of the great founder of the mechanical theory of heat, J.R. Mayer, is unheard – “Just as little as, from the connexion between the tendency to fall and motion, we can conclude that the essence of this tendency is motion, just so little does this conclusion hold for heat. Rather might we conclude the opposite, that, in order to become heat, motion – whether simple or vibrating, like light or radiant heat – must cease to become motion (Mechanik der Wärme, Stuttgart, 1867, p. 9)."

Mach denies that the discovery of conservation of energy proves that heat is not a substance:

If anyone today should still wish to think of heat as a substance, we might allow that person this liberty with little ado. ... If, then we are astonished at the discovery that heat is motion, we are astonished at something which has never been discovered. It is quite irrelevant for scientific purposes whether we think of heat as a substance or not.

The connection between Mach’s philosophy of science and his anti-atomism is brought out clearly a little later in the same work:

... in the investigation of nature, we have to deal only with knowledge of the connexion of appearances with one another. What we represent to ourselves behind the appearances exists only in our understanding, and has for us only
the value of a *memoria technica* or formula, whose form, because it is arbitrary and irrelevant, varies very easily with the standpoint of our culture. ... But let us suppose for a moment that all physical events can be reduced to spatial motions of material particles (molecules). What can we do with that supposition? Thereby we suppose that things which can never be seen or touched and only exist in our imagination and understanding can have the properties and relations only of things which can be touched. We impose on the creations of thought the limitations of the visible and tangible. ... In a complete theory, to all details of the phenomenon details of the hypothesis must correspond, and all rules for these hypothetical things must also be directly transferable to the phenomenon. But then molecules are merely a valueless image.\textsuperscript{54}

While Mach seems to grant no value at all to Physical Atomism, regarding it as a useless hypothesis, he attacks Chemical Atomic Theory from just the opposite viewpoint: it places too severe a restriction on imagination by forcing us to visualize molecules as arrangements of atoms in a space of only three dimensions. Since the space in which molecules exist has nothing to do with the real physical world accessible to our sensations, why should we not permit ourselves to use as many dimensions as we like in arranging hypothetical atoms?\textsuperscript{35}

Before dismissing this suggestion as facetious, we should recall that modern physicists, who know scarcely more about elementary particles than 19th-century physicists and chemists knew about molecules, have generously endowed these particles with 'spin' and other properties which have no simple mechanical interpretation in three-dimensional space but may be interpreted with the help of extra dimensions. The justification for doing this is the same as that given by Mach: since we cannot 'see' these particles anyway, we have no reason to require that they may have only those spatial or mechanical properties that belong to macroscopic objects.

Mach rejected the notion of the heat death of the universe (Lord Kelvin's extrapolation of the Second Law of Thermodynamics), claiming that 'time' is only an abstraction from the causal relations between objects and has no meaning for the universe as a whole, so that it is nonsense to say that "the entropy of the universe increases with time".\textsuperscript{36} Here he sets himself apart from Boltzmann's position (first published in the same year, 1872) that molecular collisions lead to a secular increase in entropy, and also from the Energetics position of later years, which maintained that this entropy increase is a fundamental law of nature standing above me-
chanistic physics. Later, Mach was to move closer to Energetics on this point (see below).

Summarizing Mach's position in 1872, we may say that he has repudiated his earlier acceptance of Kinetic Theory and Physical Atomism, without however going over to the Dynamism which he had previously seen as the alternative to Atomism; he feels that the Chemical Atomic Theory is hypothetical, but could be more useful if the prejudice in favor of *visualizable* molecular models were abandoned. His sympathies lie with Pure Thermodynamics, and he disagrees with almost all his colleagues in stating that the problem of the irreversible time-evolution of the universe is "not a scientific question".36

IV. MISCELLANEOUS REMARKS (1882–1895)

Mach carried on the battle against atomism in conjunction with propaganda for his scientific method, without stopping long for detailed criticism or evaluation of the status of atomic theory. In his lecture at Vienna in 1882 on 'The Economical Nature of Physical Enquiry' 37, he said:

When a geometer wishes to understand the form of a curve, he first resolves it into small rectilinear elements. In doing this, however, he is fully aware that these elements are only provisional and arbitrary devices for comprehending in parts what he cannot comprehend as a whole. When the law of the curve is found he no longer thinks of the elements. Similarly, it would not become physical science to see in its self-created, changeable, economical tools, molecules and atoms, realities behind phenomena, forgetful of the lately acquired sapience of her older sister, philosophy, in substituting a mechanical mythology for the old animistic or metaphysical scheme, and thus creating no end of suppositious problems. The atom must remain a tool for representing phenomena, like the functions of mathematics. Gradually, however, as the intellect, by contact with its subject-matter, grows in discipline, physical science will give up its mosaic play with stones and will seek out the boundaries and forms of the bed in which the living stream of phenomena flows. The goal which it has set itself is the *simplest* and most *economical* abstract expression of facts.

In his *Science of Mechanics*, first published in 1883 228, Mach quoted without comment Hero's argument for atomism (p. 132), attributed Newton's confusion about the concept of mass to his preoccupation with atomism (pp. 239, 265), reverted uncritically to his own earlier interest in 'molecular forces' in connection with the forms of liquids 29 (p. 479),

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and finally stated again the hypothetical character of atomism (pp. 588–589):

... chemical, electrical, and optical phenomena are explained by atoms. But the mental artifice atom was not formed by the principle of continuity; on the contrary, it is a product especially devised for the purpose in view. Atoms cannot be perceived by the senses; like all substances, they are things of thought. Furthermore, the atoms are invested with properties that absolutely contradict the attributes hitherto observed in bodies. However well fitted atomic theories may be to reproduce certain groups of facts, the physical inquirer who has laid to heart Newton's rules will only admit those theories as provisional helps, and will strive to attain, in some more natural way, a satisfactory substitute.

The atomic theory plays a part in physics similar to that of certain auxiliary concepts in mathematics; it is a mathematical model for facilitating the mental reproduction of facts... As mathematical helps of this kind, spaces of more than three dimensions may be used, as I have elsewhere shown. But it is not necessary to regard these, on this account, as anything more than mental artifices. [A footnote refers to the work of Lobachevski, Bolyai, Gauss, and Riemann on generalized multidimensional spaces.]

In *The Analysis of Sensations* (1886)\(^{22d}\), Mach asserted that "the artificial hypothetical atoms and molecules of physics and chemistry" are only mental symbols for "a relatively stable complex of sensational elements" (p. 311) and chided scientists for taking refuge in atomism in order to retain the idea of 'constancy' of a body (p. 357). In an article published in English under the same title in 1890\(^ {38}\), Mach said:

I make no pretensions to the title of philosopher. I only wish to adopt in physics a point of view that need not be instantly changed the moment our glance is carried into the domain of another science; since, indeed, all must form one whole. The molecular physics of today does certainly not meet this demand.

Mach rewrote parts of his book on the history of the principle of conservation of energy for publication in English in 1894.\(^ {22b}\) He repeated his contention that the existence of a mechanical equivalent for heat does not prove that heat is motion rather than substance. But he now has a different opinion about the relation between time and entropy:

If we could really determine the entropy of the world it would represent a true, absolute measure of time. In this way is best seen the utter tautology of a statement that the entropy of the world increases with the time. Time, and the fact that certain changes take place only in a definite sense, are one and the same thing.

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This is exactly the suggestion made by Boltzmann in 1897 in his reply to Zermelo’s criticism of the H theorem, although Boltzmann uses it for a different reason. A bounded mechanical system must, according to Poincaré’s recurrence theorem, return eventually to its original configuration, so that its time-evolution will be cyclic. Hence the entropy of the universe, regarded as a mechanical system of particles restricted to a finite space with fixed total energy, cannot continually increase but must eventually decrease in order to return to its original value. Boltzmann suggested that the human sense of time-direction is determined by the direction of increasing entropy through the irreversibility of natural processes, and therefore any organisms living during a period in which entropy is (from our viewpoint) decreasing with time would not experience ‘time going backwards’ but would simply define time in a sense opposite to ours. (Boltzmann probably did not take this idea any more seriously than did Mach, but Hans Reichenbach thought highly of it.)

V. RECONCILIATION OF MECHANISTIC AND PHENOMENOLOGICAL PHYSICS (1896–1900)

By 1895, Mach had acquired a number of allies in his battle against atomism, including especially the adherents of Energetics. The dispute came to a head in the bitter debate between Ostwald and Boltzmann at Lübeck in 1895, and was continued for a few years thereafter in the pages of the Annalen der Physik and other journals. Although Mach took no part in this debate, it seems to be generally believed that he supported the position of Ostwald. It therefore came as a surprise to me when I read the section in Mach’s Wärmelehre (1896) in which Mach comments on the dispute and suggests that a reconciliation of mechanistic and phenomenological physics should be possible. Having already pointed out earlier the defects of the mechanistic viewpoint, he feels that something should now be said in its favour, lest the extreme phenomenology of Energetics carry the day. He mentions now with approval the Kinetic Theory, which, by representing the properties of gases and solutions in terms of statistical mass motions of molecules, has stimulated experimental investigations of the temperature-dependence of diffusion velocity, viscosity, etc., and has thereby led to the acquisition of new knowledge about these properties. “The freedom that one permits himself in as-
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assuming invisible secret motions is basically no greater than in the case of Black's assumption of a latent heat. "43

At the same time Mach carefully distinguished between attempts to find Mechanical Analogies for Thermodynamics and attempts to establish a Statistical Interpretation of the Second Law of Thermodynamics. He recognized the value of Boltzmann's discovery that the Second Law corresponds to a principle of least action44, and said that we should not, after all, be surprised, having once found that heat behaves like kinetic energy, to find also that it satisfies some other mechanical principles. The occurrence of the expression

\[ \delta \cdot \Sigma \int mv^2 \, dt \]

in Boltzmann's derivation need not be considered strange, and certainly need not be taken as a new proof of the mechanical nature of heat.45 On the other hand, Mach did not like Boltzmann's idea of explaining the Second Law by distinguishing between ordered and disordered motion, making a parallel between entropy increase and increase of disordered motion at the expense of ordered motion18; this seemed too artificial to Mach.

If one realizes that an actual analogy of entropy increase in a purely mechanical system of absolutely elastic atoms does not exist, then one can hardly resist the conclusion that a violation of the Second Law – without the help of a demon – must be possible if such a mechanical system were the actual basis of heat processes. I agree completely with F. Wald, when he says: "In my judgment the root of this [entropy] principle lies much deeper, and if it is possible to bring the molecular hypothesis and the entropy principle into harmony, then it is lucky for the hypothesis but not for the entropy theorem."46

Although Mach does not mention the recurrence and reversibility paradoxes specifically, he seems to be siding with the critics of kinetic theory who would be willing to throw out mechanical models if they permitted any deviations from the absolute validity of the Second Law.

When Mach wrote his Wärmelehre he must not have understood all the ramifications of Boltzmann's theory of irreversibility, for a few pages after the criticism just mentioned, he quotes approvingly Boltzmann's idea that a physical system when left to itself passes to a more probable state, in connection with the tendency toward stability in natural processes discussed by Fechner, Hering, Avenarius, and Petzoldt.47 Mach
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does not seem to realize that he is thereby conceding the validity of an important part of the Statistical Interpretation of the Second Law.

Mach's earlier judgment on atomism was elaborated, with special reference to the Chemical Atomic Theory, in the same book:

Modern atomistics is an attempt to make the substance concept in its naivest and rawest form — that the body is absolutely permanent — the basis of physics. The heuristic and didactic value of atomistics, which lies in its perspicuousness [Anschaulichkeit] setting into motion the simplest, easiest, most concrete elementary and instinctive functions of fantasy and the intellect, should certainly not be denied. It is significant that Dalton, who was a schoolmaster by trade, revived atomistics. But atomistics, with its childish and superfluous accompanying pictures, stands in sharp contrast to the other philosophical developments of modern physics. It would undoubtedly be possible, just as with the Black substance-picture, to extract from atomistics the essential factual kernel and get rid of the superfluous accompanying pictures. Among these realities belong the concepts of definite combining weights, and of multiple proportions. Only with some effort could the simple volume relations of compounds also be represented [without atomic theory]. Above all other things, however, atomism represents the principle that the elements emerge unchanged from their compounds. How little this 'invariability' of a body corresponds to the original raw substance concept, will become clear. Through the progress of 'Stereochemistry' atomistics has again gained ground.

The attempt to eliminate atomism from Chemical Atomic Theory was made by Wald, the year after the publication of Mach's book, and Mach quoted it in a footnote added to the second edition in 1900. At the same time he amplified his remark about stereochemistry, and praised Stallo's book The Concepts and Theories of Modern Physics (1882), which he has just learned of through a reference in Bertrand Russell's book The Foundations of Geometry. He also replied to Boltzmann's article in favor of atomism, and denied that he advocates a continuous space-filling matter.

Mach and Boltzmann were both teaching in Vienna at this time, and Boltzmann took over Mach's lectures on philosophy of science when Mach retired. It would be of great interest to know something about the personal relations of the two men at this time, since their views on atomism have usually been considered to be irreconcilable. Some evidence on this point is provided by the recollections of Philipp Frank: There was always this interesting point: what was the relation between Mach and Boltzmann? This is a point which of course plays a great role in the history.
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of modern physics, and has become rather a political issue in the Russian literature. In the Russian literature we find it sometimes said that Mach was responsible for the suicide of Boltzmann. It is said that Boltzmann was so desperate about the rejection of atomic theory by physicists, resulting from Mach's attacks on it, that he took his life. As a matter of fact this could hardly be true, since Boltzmann was himself, philosophically speaking, rather a follower of Mach. Boltzmann once said to me, "You see, it doesn't make any difference to me if I say that the atomic model is only a picture. I don't mind this. I don't require that they have absolute, real existence. I don't say this. 'An economic description,' Mach said. Maybe the atoms are an economic description. This doesn't hurt me very much. From the viewpoint of the physicist this doesn't make a difference," Boltzmann had a philosophical viewpoint which did not require that you believe in the real existence of atoms. And there wasn't, I would say, any opposition to Boltzmann's physics from the viewpoint of Mach. This opposition existed only, so to speak, in the philosophical realm. Also, strange as it was, in Vienna the physicists were all followers of Mach and followers of Boltzmann. It wasn't the case that people would hold any antipathy against Boltzmann's theory of atoms because of Mach. And I don't even think that Mach had any antipathy. At least it did not play as important a role as is often thought. I was always interested in the problem, but it never occurred to me that because of the theories of Mach one shouldn't pursue the theories of Boltzmann.

I wouldn't say, either, that Mach was against the statistical interpretation of thermodynamics. The views of Mach agreed with those of the American, Stallo. He believed that there are no sufficient experimental proofs for assuming the existence of atoms. From the philosophical viewpoint, he rejected them, for reasons which are really similar to those of Stallo. His chief argument, I think, was always that if the atom were a mechanical object, then you could not explain, for instance, the great complexity of spectral lines. Therefore there must be something else there. Schrödinger has always been, throughout his whole life, influenced in a certain way by Mach. And I always had the idea that the atom of Schrödinger is not the atom in the sense of the atomistic theory.

Individually and privately there might have been cases in which people were somehow diverted from the study of atomistic theory because they believed in the phenomenalistic theory, but I don't think that it played a great role among the productive physicists. All were more or less followers of Mach in the philosophical sense: Einstein, Heisenberg, and probably also Bohr.

VI. MACH 'SEES' AN ATOM (1903)

Stefan Meyer has reported the following incident, which occurred around 1903. The apparatus invented by Elster and Geitel, and by Crookes, had made it possible to display the flashes made by individual α particles on
a screen. Of course this does not mean that one actually sees individual atoms, but, as Meyer points out, when we say that we ‘see’ the sun we are actually reporting only our observation of light rays, and the trail back from this observation to a glowing sphere of mass $2 \times 10^{30}$ kg around which planets revolve is complicated indeed. Be that as it may, there was naturally great curiosity in Vienna to see what impression the new device would make on Ernst Mach. Whenever any of the atomists would speak of atoms to him, he would always say: “Have you seen one?” Up to then, the atomists had to admit that they had not. But now the tables were turned. Though already sick and partially lame, Mach came to the laboratory to look at the spinthariscope. When he saw the flashes, he made no hair-splitting qualifications, but said simply: “Now I believe in the existence of the atom.” An entire world picture had changed for him in a few minutes (according to Stefan Meyer).

VII. THE UNREPTANT SINNER (1910)

That should have been the end of the story, except that in real life things never turn out quite as neatly. Whether Mach later had second thoughts and withdrew his rash surrender to the atomists, or whether Stefan Meyer’s memory has retrospectively changed the importance or the date of the incident, we do not know. In any case, Mach’s last published statements give no indication that he has changed his mind about the existence of atoms.

In 1909, Planck attacked Mach in the lecture mentioned at the beginning of this article. In his reply, Mach reiterated his opinion that atomism is a “hypothetical-fictive physics” and repeated his objection to Boltzmann’s statistical interpretation of the Second Law of Thermodynamics. He associated himself with Ostwald as a follower of Rankine’s views on the superiority of descriptive to explanatory science, ignoring the fact that Rankine himself devoted considerable effort to developing a molecular-vortex theory of heat. In this essay, written at the age of 72, Mach gives the impression of being a sinner on his deathbed, refusing to be converted by Father Planck to the faith which all his colleagues have accepted; rather than join the company of believers in the reality of atoms, he prefers to maintain to the end his freedom of thought. He reiterated this disbelief in the preface to his book Physical Optics in 1913.
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At about the same time, Einstein talked to Mach about atomism, and asked him whether he would not accept the atomic theory if (as now seemed likely) it turned out to be the only one that could account for the experimental facts. There are at least three extant accounts of this meeting, all of which agree in essentials: Mach said that he would agree that the atomic theory was the best and most useful hypothesis for physics, without necessarily accepting the 'real existence' of atoms.

VIII. SUMMARY AND CONCLUDING REMARKS

Atomism, as Mach knew it, took several forms in the late 19th century. First was the Atmospheric Atom Model, defended by Fechner and Mach's teacher Ettingshausen. After initially accepting this model, Mach rejected it, as did almost all his contemporaries. Second was the Kinetic Theory, which Mach regarded as a hypothesis which led to some useful results but had been accorded too much attention by physicists because of their confusion about the logical implications of the equivalence of heat and work. Third was the Chemical Atomic Theory; Mach thought that its successful results did not depend on the existence of atoms and could be formulated also in a non-atomistic system. Fourth was Dynamism, which Mach rejected initially and never mentioned again, except obliquely when he denied that he advocated a continuum theory of matter. Fifth was Physical Atomism, which Mach would grant no more than heuristic value.

The sixth theory on our list, Pure Thermodynamics, was separate from atomism but not hostile to it. Mach tacitly approved of this theory though he contributed nothing to it himself. The tradition of Pure Thermodynamics has continued down to the present, as may be seen by looking at the recent papers on Caratheodory's method in the American Journal of Physics; yet, ironically, this is the theory which is now recognized by its practitioners as mainly heuristic, whereas Mach apparently thought it could be developed as a research method; while atomic theory, which Mach considered heuristic, remains at the frontiers of new knowledge.

The only part of mechanistic physics to which Mach gave his unqualified approval (though only in a few words), the attempts to find Mechanical Analogies for Thermodynamics, has completely dropped out of sight in the 20th century. Attempts to find a Statistical Interpretation of the
Second Law of Thermodynamics, on the other hand, have been vigorously pursued despite Mach's skepticism; Boltzmann's \( H \) theorem and Maxwell's demon still find a prominent place in modern textbooks. Some of the vehemence of Planck's attack on Mach may be explained by the fact that Planck himself was only a recent convert to Boltzmann's statistical theory of entropy, having previously opposed it.\(^{54}\) Planck had reluctantly forced himself to use Boltzmann's methods in order to provide a theoretical justification for his radiation formula, and apparently he thought that everyone who still believed that the principle of increasing entropy is absolutely rather than statistically true must be counted as an enemy of modern quantum physics.

Energetics, as a theory of physics, is dead, despite periodic attempts at reviving it. Mach, though sympathetic to many of its goals, did not give his full support to it. Empiriocriticism, Mach's own scientific methodology, has been acknowledged as the forerunner of modern logical positivism and operationalism, and has sometimes been credited with stimulating the theories of relativity and quantum mechanics. It has survived as one possible basis for scientific method, though certainly not the only one.

Having discussed in some detail Mach's views on atomism in relation to 19th-century atomic theories, I would like to conclude by pointing out what seems to be a lack of relationship that one might expect. While Mach was not alone in expressing a distaste for crude mechanistic models in physics, his critique of atomism seems to issue from a philosophical viewpoint that is less in touch with the contemporary state of science than were the objections raised by the other anti-atomists. Mach seemed to have little interest in such problems as the paradox of specific heats, or in the detailed comparison of theory and experiment, or even in the logical consistency of atomic models. He left this sort of criticism to writers such as Stallo, whose book \textit{The Concepts and Theories of Modern Physics} (1881) contains a devastating indictment of the kinetic theory of gases. (Mach's endorsement of Stallo has already been noted.\(^{21}\)) For Mach the unreality of atoms, or rather of any entity that was not subject to sense observation, was a basic axiom; the validity of the axiom could not be affected by that fact that certain phenomena could only be explained, at a particular time, by an atomic theory. On the other hand, Mach was perfectly willing to admit the utility of atomism as a hypothesis.
In this respect, Mach's anti-atomism was both more and less strong than Ostwald's. Ostwald, in the 1890's, wanted to eject atomism from science on scientific grounds and replace it by other hypotheses such as Energetics; this was too extreme a position for Mach to follow, as we have seen in the section in *Wärmelehre*. But later, after the work of Einstein, Smoluchowski, and Perrin on Brownian movement had provided new scientific evidence for atomism - evidence which made no impression at all on Mach's views - Ostwald changed his mind and was willing to rehabilitate atomic theory.\(^5\) Mach, as we have seen, still refused to be converted, and rejected atomism as late as 1913 in the preface to his *Physical Optics*.

It is just because of this dogmatic character of Mach's anti-atomism - his refusal to take account of scientific evidence - that I think the final verdict has to go against Mach's methodology, even with the many historical factors taken into account. While I have only considered atomic theory in this article, a similar case can be made on the basis of Mach's views on mechanics.\(^6\) It must be emphasized that while Mach's writings may well have prepared other scientists to accept the revolution in the conception of the nature of matter that occurred in the 20th century, Mach himself was not prepared for that revolution, and he played essentially no constructive role in bringing it about. The path to quantum mechanics did *not* lead through Pure Thermodynamics or Energetics or Empirio-criticism, but rather through just the kind of naive juggling of mechanistic hypotheses about atoms and molecules which Mach himself deplored. Similarly, the debt of Einstein's relativity to Mach has been overestimated, even by Einstein himself (perhaps intentionally). If Planck, Einstein, Bohr, De Broglie, Heisenberg, Schrödinger, and Dirac had followed Mach's rules for constructing scientific theories, they would hardly have been able to arrive at the results they did.

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5 M. Planck, Neue Bahnen der physikalischen Erkenntnis. Rede in der Berliner Universität anlässlich der Übernahme des Rektorats am 15.10.1913, Norddt. Buchdr., Berlin, 1913; Barth, Leipzig, 1914. English translation in Philosophical Magazine 28 (1914) 60 (also in A Survey of Physical Theory; the quoted passage is slightly different, on p. 54).

6 This model has obvious similarities to the ordinary theory of positive and negative electric charges, and in fact both theories developed together in the 18th century from a common origin in Newton's theory of gas pressure. See I.B. Cohen, Franklin and Newton, American Philosophical Society, Philadelphia, 1956.


8 See for example J.C. Maxwell, 'Address to the Mathematical and Physical Sections of the British Association' (Liverpool, September 15, 1870); The Scientific Papers of James Clerk Maxwell, Cambridge University Press, Cambridge, 1890, Vol. II, p. 223.


10 See for example the review by C.A. Coulson, 'Interatomic Forces: Maxwell to Schrödinger', Nature 195 (1962) 744.


15 G.H. Bryan, 'Researches related to the connection of the Second Law with Mechanical Principles', The Laws of Distribution of Energy and their Limitations', Reports of the British Association for the Advancement of Science 61 (1891) 85; 64 (1894) 64.

16 See letters to P.G. Tait, December 1, 1873, and October 13, 1876, in C.G. Knott, Life and Scientific Work of Peter Guthrie Tait, University Press, Cambridge, 1911, pp. 115 and 222.

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21 See ‘Vorwort zur zweiten Auflage’ of Mach’s Wärmelehre, August 1899. See also the note on page 430 of the 4th edition.

22 The major works of Mach in which his views on atomism are expressed are the following:

(a) Compendium der Physik für Mediciner, Wilhelm Braumüller, Wien, 1863 (I am indebted to Professor Erwin Hiebert for showing me a copy of this rare book, and pointing out its significance).


(d) Beiträge zu Analyse der Empfindungen, G. Fischer, Jena, 1886; 9th ed., 1922; English translation, Contributions to the Analysis of the Sensations, Open Court Publishing Company, Chicago, 1897; Dover reprint 1959.


(f) Die Leitgedanken meiner naturwissenschaftlichen Erkenntnislehre und ihre Aufnahme durch die Zeitgenossen, Barth, Leipzig, 1919 (reprinted from Physikalische Zeitschrift 11 (1910) 599, and Scientia 7 (1910), nr. 14).

For a more complete list of works by and about Mach, see J. Thiele, ‘Ernst Mach-Bibliographie’, Centaurus 8 (1963) 189.

23 Compendium, p. vi.


26 Ibid., p. 15.
27 Ibid., pp. 92-94.
28 Ibid., p. 179.
29 E. Mach, 'Über die Molecularwirkung der Flüssigkeiten', Sitzungsberichte der kaiserlichen Akademie der Wissenschaften in Wien 46 (1862) 125.
30 See the note added to the second edition of ref. 22b, p. 86 in the English translation.
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33 Ibid., p. 47.
34 Ibid., p. 49.
36 Ibid., p. 63.
38 The Monist 1 (1890) 48.
41 See also the English translations of two of Boltzmann’s articles, ‘The Recent Development of Method in Theoretical Physics’ and ‘On the Necessity of Atomic Theories in Physics’, The Monist 11 (1900) 226; 12 (1901) 65. (I am indebted to Lewis Auerbach for this reference.)
42 See for example the statement of A. Sommerfeld, quoted in the translator’s introduction to Boltzmann’s Lectures on Gas Theory.
43 Wärmelehre, p. 362.
45 Mach, Wärmelehre, p. 364.
47 Wärmelehre, p. 381.
48 Ibid., pp. 428-29.
49 Wärmelehre, 4th ed., p. 357.
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