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ERNST MACH AND THOUGHT EXPERIMENTS IN SCIENCE EDUCATION

Michael R. Matthews

INTRODUCTION

Ernst Mach (1838-1916) was one of the great philosopher-scientists of the pre-modern period. He was a truly Renaissance Man: a master of most European languages; a reader of the Greek and Roman classics; a physicist whose contribution to diverse fields such as electricity, gas dynamics, thermo-dynamics, shock waves, optics, energy conservation and mechanics, were outstanding; a historian and philosopher of science; a psychologist; the Rector of Prague German University; a member of the Austrian parliament; and the writer of wonderful, lucid prose.[1] By all accounts his character was as pleasant as his intellectual achievements were grand. William James, who met Mach in 1882, wrote to his wife that

> I don't think anyone ever gave me so strong an impression of pure intellectual genius. He apparently has read everything and thought about everything, and has an absolute simplicity of manner....that (is) charming (Feberabend 1981, p. 64).

He was a socialist, and a liberal-humanist in the very centre of the arch conservative, and Catholic, Austro-Hungarian Empire.

Mach's first publication was in 1859, the year of Darwin's The Origin of Species; his last was published posthumously in 1921, the year of Einstein's Relativity: the Special and General Theory. He contributed to the accomplishments of Boltzmann, Maxwell, Planck, Poincare, Einstein, and indeed most of the physicists who were preparing the ground for the revolution of modern physics. This contribution is echoed in such common-place terms as Mach principle, Mach bands, Mach angle and Mach number. Einstein often acknowledged the debt he owed to Mach for the formulation of his relativity theories (Hoffmann 1977, p. 78, Holton 1970).

1. Accounts of Mach's life and achievements can be found in his enteries in the Encyclopedia of Philosophy, and the Dictionary of Scientific Biography. Additional material can be found in Blackmore (1972), and Cohen & Seeger (1970).

Mach's contribution to philosophy was enormous. This was through his influence on the early members of the Vienna Circle - Rudolph Carnap, Phillip Frank, Moritz Schlick and Otto Neurath. Indeed this group initially met as the "Ernst Mach Society" (Ayer 1959). Whether this contribution was helpful or harmful has been the subject of fierce partisan debate. Mach's philosophy has been attacked both from the Left and the Right. Lenin's Materialism and Empirico-Criticism was directed squarely against what he saw as Mach's Berkelian-like idealist tendencies. J.D. Bernal popularised these criticisms in the West (Bernal 1959). On the other side Karl Popper has been a long-standing critic of Mach's instrumentalism and phenomenalism (Popper 1959, p. 59). Elie Zahar is one of the many Popperians to repeat these charges (Zahar, 1977). Paul Feyerabend has made a concerted effort to rescue Mach's philosophy from the attacks of these critical rationalists (Feyerabend 1981, Vol. 2). This effort has been somewhat in vain: Mach's reputation among philosophers is not high. When the empiricist tide ebbed, it took with it Mach's philosophical reputation. This was unfortunate as he was much more sophisticated than many of his critics have recognised.

I do not wish here to rehearse these philosophical arguments. I wish to draw attention to Mach's long-overlooked contribution to educational debate, and particularly to his proposals for science education. These are strikingly modern and of great relevance to constructivist-inspired debates in science education.

Mach is noteworthy in his period for being a major scientist who concerned himself with educational matters: most did not. The only comparable scientist is Alfred North Whitehead, whose Aims of Education appeared in 1929. Mach was the son of a school teacher. He was early on influenced by the ideas of the German philosopher-psychologist-educationalist Johann Friedrich Herbart (who had succeeded to Kant's chair at Konigsberg, and who almost followed Hegel at Berlin). In 1887, with G.B. Schwalbe, Mach founded a journal devoted to issues in physics and chemistry instruction (Zeitschrift fur den physikalischen und chemischen Unterricht). He edited and contributed to this journal through to his retirement in 1900. Whilst at Prague German University from 1867 to 1895 he taught courses on high school physics teaching. He lectured extensively to school teacher associations. He wrote many physics textbooks; books that were used at school and university by nearly all the great European scientists of the latter half of the nineteenth century.

Mach's efforts on behalf of science education were of course conducted at a time when the very teaching of science in high schools was a matter of dispute. In England, Thomas Huxley had been arguing with Matthew Arnold for the recognition of science in a liberal education. In Germany the classical Gymnasium excluded the teaching of science and mathematics.

Elite education was regarded as a classical and literary education. The president of the Berlin Academy had just a century earlier (1752) proposed establishing a city in which only Latin would be allowd to be spoken, this to train and discipline the minds of children. Science was taught in designated schools - Realgymnasiums, and there it was taught in a most Prussian manner (Arnold 1868). Mach's own university teacher, Ettinghausen, in the 1850's became the first professor in a German university to introduce student laboratory exercises as a supplement to lecture-demonstrations in science. It was this fact-laden, cook-book style of science education that Henry E. Armstrong was at the time arguing against in England (Armstrong 1903).

Mach's theory of science, his view of what science is, in large measure determined his approach to science pedagogy. This approach has a number of central themes that are surprisingly modern, the more surprising given the avowed empiricist commitments of Mach. These themes include the following:

1. Science is fallible, it does not provide absolute truths.
2. Science is an historically conditioned intellectual activity.
3. Science ought to be unified, the compartmentalization of the disciplines is artificial.
4. Scientific literacy is an integral part of any education.
5. Scientific theory is best understood if its historical development is understood.
6. Individual scientific learning is enhanced if it proceeds historically.

One can see in this constellation, elements of Thomas Kuhn, Jean Piaget, Gerald Holton and the constructivist school of science education. The rock-bottom claims are that all human cognition is radically historical, and that its adequacy is to be tested ultimately in some form of experience.

For Mach all intellectual puzzles - be they about why people like to be ruled by a king, why there are wealthy and poor classes, or why we believe in the conservation of energy - are to be resolved by the help of history. In science especially, "there is only one way to enlightenment: historical studies" (Mach 1911, p. 16). Science teaching was to be both practical and historical. Without experience and its conceptualisation, there are no puzzles; without history, there are no satisfying solutions.

> Whoever knows only one view or one form of a view does not believe that another has ever stood in its place, or that another will ever succeed it; he neither doubts nor tests (Mach 1911, p. 17).

Mach clearly saw that without a mathematical and scientific education "a man remains a total stranger in the world in which he lives" (Mach 1943, p. 359). Beyond this understanding, such education developed the strengthening of reason, judgment and the promotion of imagination. These abilities were enhanced to the extent that the curriculum was limited. "I know nothing more terrible than the poor creatures who have learned too much" (Mach 1943, p. 367). Of these Mach said

> What they have acquired is a spider's web of thoughts too weak to furnish sure supports, but complicated enough to produce confusion (Mach 1943, p. 367).

A novel aspect of Mach's approach to science education was the stress that he placed on pupil's participation in thought experiments (Gedankenexperimente). He said of this that

> Experimenting in thought is important not only for the professional inquirer, but also for mental development as such (Mach 1976, p. 143).

Not only the pupil, but the "teacher gains immeasurably by this method". It enables the teacher to learn what grasp students have of basic concepts and their interrelations. This stress on pupil's thought experimentation is similar to Joseph Novak's contemporary advocacy of concept mapping as a way for teachers to understand the thought patterns of their students.

Each issue of the pedagogy journal that he co-established carried thought-experiment exercises for classroom use. Such problems as a beaker of water in equilibrium on a balance has a suspended mass lowered into it: what happens to the equilibrium? Or a stoppered bottle with a fly walking on its base is in equilibrium, what happens when the fly hovers?

It is noteworthy that Mach the empiricist and sensationalist - who has been attacked by Karl Popper for the "obscruranticism" of his instumentalism (Popper 1963, p. 100), and by William Shea for his "Teutonic rigour" that blinded him to non-empirical achievements of Galileo (Shea 1977, p. 82) - was among the first to recognise the centrality of thought experiments in the history of science. He detailed the role of thought experiments in the achievements of Galileo, Newton, Huygens, Carnot, Joule and others.

Some thought experiments exposed conceptual contradictions in a theory. Such was Galileo's famous demonstration that the Aristotelian "speed of fall depends on weight" axiom was contradictory. He asked his audience to imagine a heavy and a light body falling separately, then to join them and predict what will happen. There is a contradiction: the composite ought fall slower than the original heavy body because it is retarded by the light body, but it also ought to fall faster because it is heavier than the original body (Galileo 1954, p. 60).

Other thought experiments concerned circumstances that could not be realised. Such was Galileo's criticism of the Aristotelian categories of natural and violent motions whereby for heavy bodies their natural motion was caused by a tendency to move to the centre of the earth. He asked his audience to envisage a stone dropped in a well, and then the well progressively deepened until it went through the earth's center and to the other side. What happens now to a dropped stone: does it stop at the centre or pass beyond? Once more conceptual problems are highlighted by imaginative constructions.

As with practical experiments, the method of variation is characteristic of thought experiments. Here we extrapolate from behaviour in known domains to that in unknown ones. Such extrapolations may lead to paradoxical outcomes. Mach recognised the importance of abstraction in science. Of thought extrapolations, Mach said

> Physically such a process is often impossible to carry out, so that we may speak of it as an idealization or abstraction (Mach 1976, p. 140).

The beginning of thought experimentation is to have students guess the outcome of an experimental arrangement. How do we obtain a square double the area of a given one? How do we make a pendulum swing with twice its period? Mach himself in a lecture on the speed of light came close to performing Einstein's classic thought experiment whereby the common understanding of the simultaneity of events was shown to be paradoxical (Mach 1943, p. 48).

Interestingly, given this train of intellectual events, Mach had observed in the above lecture that

> new thoughts do not spring up suddenly. Thoughts need their time to ripen, grow, and develop in, like every natural product; for man, with his thoughts, is also a part of nature (Mach 1943, p. 63).

For Mach the promotion of intellectual creativity, imagination and judgment by thought experiments was also a way in which the then wide gulf between a humanities and a scientific education could be bridged.

> The planner, the builder of castles in the air, the novelist, the author of social and technological utopias is experimentating with thoughts (Mach 1976, p. 136).

So too was the mathematician.

> The change and motion of figures, continuous deformation, vanishing and infinite increase of partiuclar elements here too are the means that enliven enquiry, tell us about new properties and promote insight into their connections. It is to be assumed that the method of physical and thought experiment developed first in this simply accessible and fruitful field and spread from there to the natural sciences (Mach 1976, p. 145).

Mach knew that "thought experiment is in any case a necessary precondition for physical experiment (Mach 1965, p. 136). He saw clearly that the "close conjunction of thought with experience has built modern natural science (Mach 1976, p. 146). Science education was to foster these imaginative and intellectual abilities.

> I would be satisfied if every young student could come into living contact with and pursue to their ultimate logical consequences merely a few mathematical or scientific discoveries (Mach 1943, p. 368).

This would be done only after the subject matter is made familiar by pictures and experiment. Geometrical experience should precede Euclid. But with this background, the final stages of a school education ought consist of "an appropriate selection of readings from Galileo, Huygens, Newton etc. (Mach 1943, p. 368). Not to learn dates and experiments, but to absorb and understand something of their style; to understand their theory. Mach agrees that "enquiry cannot be taught".

> However, the examples of great enquirees are very suggestive, and practicing thought experiments after their model as briefly indicated above is bound to be beneficial (Mach 1976, p. 146).

The course of twentieth century physics confirms the importance of thought experiment: Maxwell's demon, Schrodinger's cat, Einstein's train, Heisenberg's gamma-ray microscope - all of these are the imaginative constructions, extrapolating from the known, that Mach championed. Despite this rich and important heritage, few people since Mach have paid attention to the role of thought experiment in science education. It is characteristic of the neglict of Mach, that a rare, and excellent, recent publication on thought experiments and science education does not make mention of him (Helm et. al. 1985).

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