ON THOUGHT EXPERIMENTS

ERNST MACH

Translated and adopted by W. O. Price and Sheldon Krimsky [1]

TRANSLATOR'S INTRODUCTION

As a philosopher, Ernst Mach is best known for his contributions to positivism. The role of science in Mach's view is to provide the most economical classification of the phenomena; it is "the economy of thought." In *The Science of Mechanics* Mach criticized Newton on the grounds that the latter introduced metaphysical fictions to account for certain spatial effects. Mach excoriated absolute space and absolute time from classical mechanics. Our concepts must be closely linked to the facts. He also rejected atoms as ontological realities, although in his later years he conceded that atomic theory was a convenient means of organizing a variety of experimental effects.[2]

But unlike many of the sensationalists who preceded Mach and positivists who succeeded him, he was neither inductivist nor anti-theoretical in his philosophy of science. It was Mach after all who introduced an untested and perhaps untestable assumption to explain Newton's rotating bucket experiment, namely, the gravitational effect of the distant stars.

While clearly rejecting the innatist theory of Descartes and the a priorist philosophy of Kant, Mach extolled the virtue of human reason. There is no clearer illustration of Mach's anti-inductivist views and his emphasis on pre-observational conjectures and reasoning in scientific investigation than in his writings on thought experiments.

Every step an investigator takes is guided by theory. Every experiment performed is already worked out in thought. Speaking of both Comte and Mach, Philipp Frank noted: "These men knew very well that there must be

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a theoretical starting point, a system of principles constructed by the human imagination in order to compare its consequences with observations." [3]

In his essay "On Thought Experiments" it is not ideas which are judged to be innate in man but rather the propensity to experiment. While all experiments are guided by theory, not all experiments require a laboratory. Some can be carried out exclusively in the imagination and even if they can be performed their actualization is superfluous. Mach emphasized the value of thought experiments as techniques of discovery (Carnot's Cycle) as well as critical tools of investigation (Galileo's critique of Aristotelian dynamics). By the use of *Gedankenexperimente* ideas are tested in thought before they even reach the laboratory.

While experiments in the imagination had been performed centuries prior to Mach, it was he, in spite of his empiricist tradition, who recognized their special significance for science. Thought experiments with their idealizations and hypothetical experimental arrangements often require one to make a radical departure from the facts. The intellect takes a leap, sometimes aided by empirical results but often guided only by pure imagination.

Mach's first essay on thought experiments appeared in an instructional journal of physics and chemistry (1896-1897). From his informal style of writing, the rapid jumps between the ideas and the sketchiness of his examples it is likely that the essay was first delivered as a lecture to an audience comprised predominantly of students. Eight years after its publication, the article was rewritten and adapted for a book entitled *Erkenntnis und Irrtum* (Cognition and Error).[4]

In the rewritten essay, Mach refined his ideas about thought experiments and expanded the historical examples. The basic theme of his original essay lay intact. The translation which follows is based upon the text of his first essay in 1897.

The translators took some editorial license in those cases where a departure from the literal meaning was necessary to preserve the continuity of the author's thoughts as well as to make philosophical and scientific sense.

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REFERENCES

[1] The original text of the translation is from *Zeitschrift für den physikalischen und chemischen Unterricht,* Vol. X (January, 1896-1897), pp. 1-5.
[2] Erwin Hiebert reviews Mach's changing attitudes towards atomism in "The Genesis of Mach's Early Views on Atomism," *Ernst Mach: Physicist and Philosopher,* Boston Studies, Vol. VI, ed. by Robert S. Cohen and Raymond J. Seeger (Dordrecht, Holland: D. Reidel, 1970). For Mach's later views on atomism see his published address "The Guiding Principles of My Scientific Theory of Knowledge and Its Reception by My Contemporaries," in *Physical Reality,* ed. by Stephen Toulmin (New York: Harper Torchbooks, 1970).
[3] See: "Einstein, Mach and Logical Positivism," in *Albert Einstein: Philosopher-Scientist,* Vol. 1, ed. P. A. Schilpp (New York: Harper and Row, 1959), p. 278.
[4] For the most up-to-date and complete bibliography of Mach outlining all the editions of Mach's publications see Joachim Thiele, "Ernst-Mach Bibliographie," *Centaurus,* Vol. VIII (1963), pp. 189-237. A revised and abridged version of Thiele's bibliography appears in Appendix E, *Boston Studies,* Vol. VI, *op. cit.*

If we observe how a child, who has reached the first stage of independence, tests the sensitivity of his own limbs, how surprised he appears by his own reflection or by his shadow in the sunlight and how, by his movements, he tries to find out about those circumstances, then we must say that the instinctive inclination toward experimenting is innate for man. Without much searching, he finds within himself the basic method of experimentation, namely, the method of variation. If these natural gifts at times are lost for the adult and, so to say, have to be discovered anew, this is understandable, since people are mostly reared by society for a narrower range of interests. Without saying a word about bias, one observes that the society in which people are confined has taken over a large number of fixed and presumably sublime views about investigation.[1] In addition to the actual physical experiment, there is yet another which is conducted extensively and on a higher intellectual level, namely, the thought experiment.

The dreamer, the builder of castles in the air, the poet of social or technological utopias all experiment in thought. Even the respectable merchant as well as the devoted inventor or researcher does the same thing. Each of them conceives circumstances and associates with these the idea, expectation, or supposition of certain results; they create a thought experience. Whereas the former combine circumstances in their imagination not encountered in reality, or deem these circumstances to be accompanied by results not bound to reality, the latter, whose concepts are good copies of facts, in their thinking, stay very close to reality. Indeed, the possibility of thought experiments rests upon our ideas as being the more or less exact copy of facts. Just as when the stroking of a clock has discontinued, we are still able to count the strokes in our memory; we can still perceive in the afterimage of a lamp, details which have escaped immediate observation; we can, in recollecting, discover a feature which suddenly unveils for us the previously misunderstood character of a person. Similarly, in our recollection, we can even discover new properties about physical facts which for a long time went unnoticed.

Our own ideas are more easily and readily at our disposal than physical facts. We experiment with thought, so to say, at little expense. Thus it shouldn't surprise us that, oftentimes, the thought experiment precedes the physical experiment and prepares the way for it. Indeed, the physical investigations of Aristotle are mostly thought experiments in which the stores of experience, preserved in the memory and especially in language, are utilized. However, a thought experiment is also a necessary pre-condition for a physical experiment. Every inventor and every experimenter must have in his mind the detailed order before he actualizes it. Even if Stephenson knew the train, the rails, and the steam engine from experience, he must, nonetheless, have preconceived in his thoughts the combination of a train on wheels, driven by a steam engine, before he could have proceeded to the realization. No less did Galileo have to envisage in his imagination the arrangements for the investigation of gravity, before these were actualized. Even the beginner learns in experimenting that an insufficient preliminary estimate, or nonobservance of sources of error has for him no less tragic-comic results than the proverbial "Look before you leap" does in practical life.

The result of a thought experiment can be so definite and decisive that any further test by means of a physical experiment, whether rightly or wrongly, may seem unnecessary to the author. The more uncertain and more indefinite the results are, however, the more the thought experiment necessitates the physical experiment as its natural continuation which must now delimit and determine the experiment. We will return later to cases of this latter type. Several examples of the former type shall be considered first.

There is no doubt, that the thought experiment introduces the greatest transformations in our thinking and reveals the most significant paths of investigation. Even if the tale of a falling apple, which Euler assumed to be true, is not to be taken literally, these thought processes were none the less quite similar to those which Euler [2] and Gruithuisen [3] knew how to demonstrate so excellently. This gradually led from the conception of Copernicus to that of Newton. The principles of both can be demonstrated historically even by diverse persons and in times far removed from one another.

Suppose a stone falls to the earth. Let us assume its distance from the earth increases. It is unnatural to contrast this continuous increase with a discontinuity in our expectations. Even from the moon's distance, the stone will not suddenly lose its propensity to fall. The large stone falls just like the small stone. Let the stone become as large as the moon. The moon also has a tendency to fall to the earth, even if it increases until it is as large as the earth. Now, our idea would lose its certitude if we were to assume that only the one is attracted to the other and not vice versa as well. Thus, the attraction is reciprocal. It also remains reciprocal with different bodies because one case merges continuously with the other.

One stone falls beside the others. The moon and earth consist of stones. By the reciprocal effect of the masses each part attracts every other part. The moon and earth are not essentially different from other heavenly bodies. Gravitation is universal. Keplerian motion is a projectile motion which is dependent upon an accelerated fall from a distance. The acceleration, in general, is dependent on distance. Kepler's laws are only ideal cases—perturbations.*

It can be seen that the basic method of the thought experiment is just like that of a physical experiment, namely, the method of variation. By varying the circumstances (continuously, if possible) the range of validity of an idea (expectation) related to these circumstances is increased. Through modification and specialization of the circumstances the idea is modified and specialized and these procedures vary.

Let us consider another developmental process. Bodies of the same temperature do not mutually interact with one another. The warmer body A (a red hot ball of iron) warms the colder body B (a thermometer) even at a distance by means of radiation, e.g., in the experiment with

* The term Mach uses is "Störungen" which in astronomy is best understood as "perturbations." (Ed.)

coaxial mirrors. If one substitutes (like Pictet) instead of A, a tin box containing a freezing mixture, then B is cooled down. Is there cold radiation? Isn't this new case the same as the former except that A and B have changed roles? In both cases the warmer body heats up the colder. If we assume A is warmer than B the temperatures become equalized. Finally, let us assume A has a lower temperature than B. Which body radiates heat to the other in the intermediate case? Doesn't the behavior of the bodies change suddenly by the transition to a uniform temperature? Both bodies radiate independently of one another and both bodies absorb independently of one another. Dynamic temperature equilibrium is discussed by Provost. Different bodies of equal temperature radiate unequal amounts of heat (Leslie, Rumford). If dynamic equilibrium holds, then a body which emits twice as much radiation also absorbs twice as much. The laws of radiation postulated by Fourier and Kirchhoff were discovered by determining experimentally those ideas which agreed with the firmly held principle of dynamic equilibrium.

As is well known, we find in the works of Stevin, Galileo and Huygens a similar series of thought experiments. These lead us to the same conclusion, namely, that questionable ideas of a view assumed reliable were established through experimentation. The most splendid thought experiment of this kind in terms of its results is probably found in Carnot's principle. The method followed by Carnot which James Thomson and William Thomson mastered yielded an almost inexhaustible fruitfulness.

It will depend upon the type and the extent of the practical experience acquired whether a thought experiment as such can be brought to a conclusion with a definite result. A colder body absorbs heat from a warmer body. A melting or boiling body is found in this case, not to become any warmer. Accordingly, for Black there is no doubt that heat upon conversion into liquid or steam becomes latent. Black can determine all the quantity of latent heat solely through the physical experiment if this is related even in form to the thought experiment. The existence of the mechanical equivalent of heat was revealed by R. Mayer and Joule through thought processes. Joule had to determine numerical values by means of experiments, whereas Mayer could derive even these, so to say, with the help of other values called to mind.

If a thought experiment has no definite result, e.g., if there is not associated with the conception of certain circumstances any clear and definite expectation of a result, then in the time between the intellectual and physical experiment we are in the habit of conjecturing. That is to say, we undertake by way of conjecture a closer and conclusive determination of the results. This conjecturing is not methodologically unscientific. We can illustrate this natural process much better with classical examples. On closer examination it becomes clear to us that this conjecturing is often the sole way of providing the form for the physical experiment (the natural continuation of the thought experiment). Before Galileo experimentally investigated the motion of falling bodies he turned to theorizing. He understood, solely through reflection, that velocity increases. His experiment only becomes possible by testing the hypothesis. In like manner Richmann's law of mixtures was a conjecture, confirmed by means of an experimental test. There are very many examples of this type.

This method of conjecturing the outcome of a given experimental arrangement also has a high didactic value. As a grammer shool child I had for a short time a teacher who, by this method, knew how to hold the student's span of interest in a superior fashion. Pisko was also another excellent teacher who, when on the occasion of a visit to his school, I observed used the same method. Not only the student but even the teacher gains a great deal from this method. By this method more than by any other the teacher becomes better acquainted with his students. While some students guess the next step others guess results which are extraordinary. Generally, the intuitively obvious will be conjectured from the given. Just as the slave in Plato's *Meno* believed that the doubling of the sides of the square also doubles the square's area, on readily hears from the elementary student that the doubling of the length of the pendulum doubles the period of oscillation. The advanced student will make less striking but analogous mistakes. Even these mistakes will gradually sharpen the feeling for the distinctions between that which is determined through association or intuition. The student will learn to discriminate the solvable from what is generally non-solvable.

Experimenting in thought is extremely important for cognitive development. The question arises, however, as to how such experiments originate. Just as every movement before it can become a voluntary one had to begin by chance, perhaps as a reflex action, likewise, it will also depend upon simply producing thought experiments through appropriate circumstances for it to become a permanent habit. For this purpose, the presentation of paradoxes is exceptionally appropriate. Not only does one learn by means of a paradox to best perceive the nature of a problem in which, indeed, even the paradoxical content is problematic, but the conflicting elements of a paradox permit thoughts no longer to come to rest. These elements produce the process which is characterized as a thought experiment. Let us consider, for example, a water beaker balanced on a scale, into which one plunges a metal ball supported by a special stand. Or let us imagine that a fly is hovering above the balanced flask. In fact, consider any of the other conceptual problems presented in this journal. The various expectations related to the individual circumstances, which in these cases are connected, might be conceptually problematic. None the less, because of this progress and clarity result.

The specific continuous variation which appeared in several of the previously mentioned classical thought experiments, reminds one vividly of the continuous change of visual imagination described by Johannes Müller [4] in his outstanding book. Müller emphasized there the identity of the creative imagination of the artist and the scientist. He has in mind, as a representative of the latter, Goethe in his morphological investigations. He considers the spontaneous independence of imagination incompatible with the laws of association about which he speaks very critically. It seems to me that the phenomena described by Müller of the continuous change of imagination are completely reconcilible with the laws of association; indeed, these can even be conceived of directly as memory states. The perspectival images of visual objects also change, as a rule, continuously. The discontinuous images only enter into association by the fact that soon this and soon that sense field begins to participate. It should be acknowledged that this interesting but little noticed point is in need of a more thorough investigation.

It was not possible in the scope of this article to analyze completely all forms and phases of thought experimentation. This must be reserved for a more thorough exposition. The remarks, herein, suggest that the thought experiment not only is of importance in the field of physics, but on the contrary, in all fields of knowledge, even where one would seek it least of all—in mathematics. Perhaps there is no contradiction if we characterize Euler's method of investigation with its great fruitfulness (for which rigorous criticism has not always kept pace) as very closely identified to those methods of a research scientist who explores a new field for the first time.

REFERENCES

[1] Even young animals can be seen experimenting. However, their sphere of interest is much more limited. A kitten curiously examines his reflection, immediately becoming indifferent upon realizing that this is no real cat. I have seen intelligent horses carefully investigating a hazardous footbridge by stamping.

[2] Euler, *Lettres à une princesse d'Allemagne,* Letter 1, p. 52.

[3] Gruithuisen, *Die Naturgeschichte, etc.* (Munich, 1910), p. 103.

[4] Johannes Müller, *Die phantastischen Gesichtserscheinungen* (Coblenz, 1826), p. 95.