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## MACH, DUHEM AND THE HISTORICAL METHOD IN PHILOSOPHY OF SCIENCE

Anastasios Brenner<sup>1</sup>

### *Introduction*

The encounter of Ernst Mach and Pierre Duhem is significant in several respects. Duhem, who had written a book on the history of mechanics, gave a lengthy and commendatory review of the latter's *The Science of Mechanics*, when it appeared in French translation<sup>2</sup>. He perceived a connection between Mach's principle of economy and his own definition of physical theory as an abstract representation of laws, and recognized his Austrian counterpart as a forerunner. In turn, Mach expressed their mutual understanding most forcefully in the Preface to the second edition of *Knowledge and Error*: "Duhem's *La Theorie physique, son objet et sa structure* [...] has given me great pleasure. I had not hoped to find so soon such far-reaching agreement in any physicist"<sup>3</sup>. The claim that the aim of science is thought economy or abstract representation opened up a new perspective with regard to traditional views. Mach and Duhem came to share several other theses regarding experimental testing, measurement and mathematization. My aim is to explore this "far-reaching agreement".

Yet there are obvious differences between the two thinkers. First, Mach allotted a good amount of space in his historical studies to methods of observation, instruments, and experimental setups, whereas Duhem focused on concepts, theories and mathematical developments. *The Science of Mechanics* provided an abundant documentation on the history of experimental techniques, and Mach did not fail to mention some apparatuses he had devised for his teaching. On the other hand, Duhem was attentive in his works to the philosophical background, the conceptual changes, presenting the contrast between descriptive and explanatory theories in a broad discursive context. In summary, they approached the goal and nature of science from different angles, and one could point to other differences in scientific research, philosophical views and political opinions.

Despite such differences, both thinkers suggested a reading in which their endeavors complement one another. Duhem seized the opportunity of his agreement with Mach to dispel some objections raised by his views: although his presentation of physics

is heavily mathematical and highly theoretical, his intention was not to overlook the empirical basis. Conversely, Mach could show how his analysis of experimental techniques threw light on the development of physics as a mathematized science. His aim was to understand the association of mathematics and the empirical world. Both Mach and Duhem contributed to our understanding of scientific activity. But how should we characterize their relationship?

Indeed, the interaction of Mach and Duhem attracted the attention of their contemporaries. One can point out two major directions in this respect. On the one hand, members of the Vienna Circle such as Philipp Frank, Hans Hahn and Otto Neurath combined the conception of Mach and Duhem in their effort to formulate a new positivism. On the other hand, Abel Rey discussed at length both thinkers in his endeavor to develop what he termed already “historical epistemology”. Here lies the point of departure of a major methodological divide — that between analytic philosophy of science and historical epistemology — which continues to this day to plague philosophers.

References to Mach and Duhem were to reappear in new settings. Their analyses were in turn called on in arguing against logical empiricism, revealing the possibility of different readings of their works. The dialogue between Mach and Duhem thus touches on issues that have come again to the fore: scientific representation as one of the options in the debate over realism, the psychology of science as renewed by cognitive science or the revival of historical epistemology.

The relation between Mach and Duhem has of course received attention. Klaus Hentschel published their correspondence with a commentary in 1988<sup>4</sup>, and the author of these lines devoted an article to Poincaré, Duhem and Mach in 1998<sup>5</sup>. In taking up the issue again, I shall follow a different approach, seeking to understand their conceptions on their own terms and to throw light thereby on current practices.

### 1. *A Singular Meeting*

Let us briefly mention the main facts concerning the encounter of Mach and Duhem. The first exchange was brought about by the almost synchronous publication of Duhem’s *Evolution of Mechanics* and the French translation of Mach’s *The Science of Mechanics*<sup>6</sup>: on 9 July 1903 Duhem sent a letter acknowledging receipt of the 3<sup>rd</sup> edition of the *Popular Scientific Lectures*<sup>7</sup>. He informed Mach that he had just completed a lengthy

review of the French translation of *The Science of Mechanics* on the proofs. This was the beginning of a correspondence, which over the next three years would reflect a remarkable mutual recognition. Thereafter the letters became less frequent and the last letter known was sent by Duhem on 10 August 1909.

This is not however the end of the story. Later references go to prove that Mach and Duhem were not indifferent to each other's research in progress. Duhem resumed the discussion with Mach over the history of mechanics in 1910, in an article on the influence of Buridan on Italian Science of the 16<sup>th</sup> Century, later published in *Études sur Léonard de Vinci*<sup>8</sup>. The catalogue of Mach's library registers a dedicated copy of one of Duhem's articles dating from 1911 concerning the Gregorian reform of the calendar<sup>9</sup>. Here Duhem makes the claim that the theory of impetus appearing in Benedetti and Galileo can actually be traced back to Buridan, thus correcting Mach's account. It is likely that this prompted Mach to reply in the 7<sup>th</sup> edition of the *Science of Mechanics*. He refers to Duhem in the very Preface dated 5 February 1912:

“With regard to history, the criticism of Emil Wohlwill was valuable for me and especially illuminating concerning the early years of Galileo [...], as well as the critical observations of P. Duhem and G. Vialati [...]. With regard to the discussions on the critique of knowledge [erkenntniskritischen Diskussionen], P. Duhem, O. Hölder, G. Vialati and P. Volkmann participated intensely and, in my view, brought about advances.”<sup>10</sup>

This acknowledgement is followed, in the body of the work, by two new sections, to which I shall return later. One could add yet another reference from Duhem's *German Science* in 1915<sup>11</sup>: although this piece clearly belongs to the war literature of the time, Mach is among the few German-language scientists not to be subjected to criticism. What we can gather from these facts is that the interaction between the two thinkers extends well beyond the correspondence as preserved. It takes us well up to the end of their lives.

There are nevertheless strong contrasts between Mach and Duhem. The two authors found themselves in different settings. Mach formulated an outlook imbued by freethinking, within the context of the Austro-Hungarian monarchy, where Catholicism was the official religion. Duhem, who elaborated his conception in the climate of secularization of the early French Third Republic, was bent on separating and also preserving religious convictions from the encroachments of science. Their positions

appear diametrically opposed. Moreover, Mach was reacting against the emphasis placed on theory and mathematics within German-language physics of the second half of the 19<sup>th</sup> century; Duhem opposed rather the experimental trend of French physics of the time. Yet both thinkers chose to highlight their agreement over their divergences, encouraging such a reading among their disciples and followers.

## 2. *A Rational Reconstruction*

Rather than follow merely the chronology of events, I prefer to seek to comprehend the significance of the relation of Mach and Duhem. It could be argued that for Mach the encounter with Duhem came too late in his career to have had a deep impact. His last major philosophical work, *Knowledge and Error*, had already been drafted. But this would be to neglect the numerous references to his French counterpart in the second edition as well as significant citations elsewhere. I believe that the dialogue with Duhem helped to shape the reception of Mach's work. As for Duhem, he was elaborating his major opus, *The Aim and Structure of Physical Theory*, when he was most engaged in the dialogue with Mach.

So, what was it that brought our two thinkers into contact? One may start by pointing to a fundamental thesis defended in common. As Mach formulated his basic idea in the preface to the French translation of his *Science of Mechanics*: "The concept of cause is replaced by that of function: a reciprocal dependence of phenomena, and their economical description becomes then the goal, while the physical concepts are but the simple means to this end"<sup>12</sup>. Duhem expressed a similar view when he claimed that physical theory does not aim to explain things as they are but to represent experimental laws. We find here the expression of a positivist, anti-metaphysical attitude.

*The Science of Mechanics*, which went through seven editions during Mach's lifetime, encountered success, but it raised controversies concerning priority as well as the role ascribed to economy of thought. In the preface to the first edition, Mach, while claiming priority for his concept of economy of thought, was careful to point to thinkers holding similar ideas such as Gustav Kirchhoff and Hermann von Helmholtz<sup>13</sup>. He returned repeatedly to this issue. He made clear that Kirchhoff was not alone in holding a descriptivist or phenomenalist attitude. He could cite in this sense Hermann Grassmann, John Stuart Mill and William Whewell. Duhem went on to add to the list André-Marie Ampère, who had indeed employed the term representation to characterize the task of the

scientist. In the 1904 edition of *The Science of Mechanics*, Mach specified that Kirchhoff's views corresponded only "in part" to his own and that his formulation was more "radical"<sup>14</sup>. Two years later he devoted an article, "Beschreibung und Erklärung", precisely to the question at hand, in which he acknowledged that the economical nature of science "was recently brought out by P. Duhem in his book *La théorie physique, son objet et sa structure* [...] in a very expressive and convincing manner"<sup>15</sup>. Reference to Duhem thus enabled Mach to emphasize the specificity of his view.

Before proceeding further, let us recall Kirchhoff's position. He wrote a series of volumes on mathematical physics. The first, which was published in 1876, was devoted to mechanics. It begins with the following statement:

"The point of departure of the presentation I have chosen differs from that generally adopted. It is usual to define mechanics as the science of forces, and forces as the causes that produce motion or tend to produce them [...]. But this presentation is vitiated by the obscurity inherent in the concepts of cause and tendency."<sup>16</sup>

Kirchhoff obviously had in mind the traditional definition given by Lagrange, according to which force or power is defined as the cause of motion. He then expounds his own presentation: "For this reason I assign to mechanics the task of describing motions that occur in nature and of describing them indeed completely [*vollständig*] and in the simplest manner possible [*einfachste*]"<sup>17</sup>.

Let us pay heed to the precise wording of this passage: simplicity alone admits of degrees; completeness is taken absolutely. Physics should no longer search for the causes nor be given over to the explanation of things. The concept of force can be dispensed with. It only serves to simplify the mathematical expressions. The position just outlined can be qualified variously as descriptivism, nominalism or positivism.

Duhem, who had been acquainted with Kirchhoff's conception, prior to reading Mach<sup>18</sup>, was likewise intent on taking this idea further. First and foremost he supposed that completeness also admits of degrees<sup>19</sup>. And as regards the reasons for choosing a hypothesis, one should include exactness or accuracy. Duhem was thus led to spell out the various criteria involved in the choice of theories.

Mach came to state clearly the scope of his concept of economy in *Knowledge and Error*:

“The term ‘description [*Beschreibung*]’ which appears already in the discussion between J.S. Mill and Whewell has been generally adopted since Kirchhoff; in contrast, let me suggest the expression ‘restriction on expectations’ as pointing to the biological importance of the laws of nature. A law always consists in a restriction of possibilities, whether as a bar on action, as an invariable course of natural events, or as a road sign for our thoughts and ideas [*Vorstellen und Denken*] that anticipate events by running ahead of them in a complementary manner.”<sup>20</sup>

The biological twist Mach gives to the idea of description is noteworthy. He pursues his reasoning over the next few pages, invoking the mental operations of simplification, schematization and idealization. He then puts forth the following conclusion:

“Only a theory that represents facts more simply and precisely than can really be guaranteed by observation (because of the influence of always numerous and complicated subsidiary circumstances) corresponds to the ideal of unambiguous determinacy.”<sup>21</sup>

It is difficult not to be struck by the similarity with Duhem’s views, and indeed in the second edition of his book, Mach would add in this place a reference to Duhem. Both thinkers were seeking to move beyond Kirchhoff. Economy of thought is a general feature of science, continually enhanced; it involves a variety of criteria: simplicity, completeness, accuracy, etc. Furthermore, Mach takes into account the activity of classifying, which again echoes Duhem.

### 3. *Intellectual Economy and Representation*

It is time we turn to Duhem’s well-known definition of theory given in *The Aim and Structure*, in which Mach saw a thesis similar to his concept of intellectual economy: “A physical theory is not an explanation. It is a system of mathematical propositions, deduced from a small number of principles, which aim to represent as simply, as completely, and as exactly as possible a set of experimental laws”<sup>22</sup>. A scientific theory is then no longer conceived as the explanation of deep causes, but as an abstract representation of laws. Duhem proceeds to explain that theory consists in a symbolic construction characterized by four operations: the definition of concepts, the choice of

hypotheses, the mathematical development, and the comparison with experiment. This series of operations is what Duhem designates by structure, and the second part of his book treats of each one in depth. One finds here the intuition of the standard view of theories, which the logical empiricists will further develop: a theory is an axiomatic system, a set of propositions deductively linked, separated into postulates and theorems, its empirical interpretation being provided by way of certain correspondence rules<sup>23</sup>.

When Duhem defines physical theory not as an explanation but as an abstract representation, he expresses a view similar to that of Mach. We are thus not surprised to see him call on the concept of economy of thought. But Duhem does not stay content with this definition of theory. He goes on to add that representation is also classification, and in the course of history, classifications are constantly improved. They tend more and more toward a natural classification. In consequence, he comes to voice implicitly some disagreement with Mach:

“Logic does not [...] furnish any unanswerable argument to anyone who claims we must impose on physical theory an order free from all contradiction. Are there sufficient grounds for imposing such an order if we take as a principle the tendency of science toward the greatest intellectual economy? We do not think so [...]. We showed how diverse sorts of minds would judge differently the economy of thought resulting from an intellectual operation.”<sup>24</sup>

Mach seized the occasion of the second edition of *Knowledge and Error* the very same year to respond in a long note<sup>25</sup>. He takes up Duhem’s contrast between, on the one hand, deep and narrow minds and, on the other, ample and supple minds. He notes Duhem’s concession that this characterization holds only in general, but he insists that one should speak only of degrees with respect to these types of minds. Mach is not ready to follow Duhem in his criticism of Maxwell’s use of mechanical models. He then reasserts his principle: “The ideal of economic and organic adaptation of compatible judgments for a subject is reached when the minimum number of simple, independent judgments is found, from which the others are a logical sequel”<sup>26</sup>.

Let us now direct our attention to the three terms that qualify representation in Duhem’s definition of theory: simplicity, completeness and exactness. It is not difficult to understand why Duhem brought them up: he had rejected the Newtonian method of inductions as well as the procedure of crucial experiment, in summary the traditional



schemas of justification. Hypotheses are now freely chosen, which does not mean that they are arbitrary; the theorist must motivate his choice. Hence the appeal to rational criteria. I do not have time to dwell on what Duhem has to say on each of these notions<sup>27</sup>. Suffice it to recall what belongs to exactness or accuracy in order to understand what he is after:

“The various consequences [...] drawn from the hypotheses may be translated into as many judgments bearing on the physical properties of the bodies [...]. These judgments are compared with the experimental laws which the theory is intended to represent. If they agree with these laws to the degree of approximation corresponding to the measuring procedures employed, the theory has attained its goal.”<sup>28</sup>

Accuracy in physics is the agreement within the accepted degree of approximation. Duhem is led to distinguish between truth in ordinary contexts and truth in physics. He goes as far as to advocate dispensing with truth altogether. In other words the scientist must take into account the exact nature of the procedure of verification or confirmation. Accuracy, as indeed other criteria, must be related to the operations constituting scientific activity. It is interesting to note that Duhem explicitly acknowledged his debt on this point to earlier scientists, among others Kirchhoff and Mach, thus setting the representative view within a broad historical context<sup>29</sup>.

#### 4. *The Historical Analysis of Scientific Concepts*

We have mentioned several references to Duhem in *Knowledge and Error*. One reference stands out, as it was set directly in the text of the second edition and, moreover, in the conclusion to the chapter “On the Psychology and Natural Development of Geometry”:

“The history of science shows that a correct new insight correctly reduced to its foundations may become more or less confused in time, appear incompletely or in distorted form or even be altogether lost to some enquirers, only to reappear in full blaze later. A single discovery and utterance of an insight is not enough. Often it takes years and centuries to develop general thinking habits to the point where the insight in question can become common property and stay permanently alive. This is

shown with especial elegance by Duhem in his detailed investigations on the history of statics.”<sup>30</sup>

Mach is referring to Duhem’s research as presented in *Les origines de la statique*<sup>31</sup>. The later had found in Jordanus Nemorarius, a 13<sup>th</sup>-century medieval savant, the concept of gravity *secundum situm*, which would play an important role in the later development of statics. This result would lead Duhem, in a series of historical studies, to formulate a new view of the birth of modern science. As analytic philosophy of science later came to discard the context of discovery, it is worthwhile to emphasize that Mach was intent on grounding his “psychology of research” on the history of science.

Let us turn to the two new passages, which were added in appendix to the 6<sup>th</sup> edition of Mach’s *Science of Mechanics*, published in 1908, and were incorporated directly in the body of the text in later editions. Mach expanded notably chapter one, section five: “Retrospect of the Development of Statics”, which begins with the following statement: “Knowledge of the development of a science consists of the study of the documents in their historical order and their mutual dependence”<sup>32</sup>. He then summarizes Duhem’s findings concerning Jordanus Nemorarius and Leonard da Vinci. He does not fail to recall Duhem’s thesis according to which “the continuity between ancient statics and modern statics was never interrupted”<sup>33</sup>. Finally, Mach directs the reader, who wants to know more, to Duhem’s book, which he qualifies as “brilliant [*prächtiges*]”. He does however express some reservations over the positive role ascribed to Aristotle. If Duhem had started by holding an Aristotelian point of view, he later came to emphasize the break with Aristotle, which he would locate in the late 14<sup>th</sup> century.

The second passage, chapter two, section one: “Galileo’s Achievements” commences thus: “Let us now ask ourselves what insights Galileo handed down to us”<sup>34</sup>. Mach is basing his account on an article Duhem published in 1905 on the problem of free fall<sup>35</sup>. He readily adopts the interpretation given by Duhem of Descartes’s contribution to mechanics. But he voices a difference of opinion concerning Duhem’s description of Galileo’s scientific practice. What Mach emphasizes is that Galileo was significantly not concealing something mysterious behind the concept of force<sup>36</sup>. It is true that Duhem had a tendency to diminish Galileo’s achievements in favor of medieval authors. But he also held that the truly representative conception became prominent only recently.

In the opening pages of *The Aim and Structure*, Duhem claims to provide “a simple logical analysis of the method by which physical science makes progress”<sup>37</sup>. Yet his book

contains a large amount of history. One finds numerous examples taken from the history of physics as well as a general interpretation of progress as a continuous process. History also enables us to go beyond the limits imposed on logical analysis. This association of history and logic is perhaps what is most astonishing for the modern reader. We are used to separating the historical study of science from the logical analysis of its language.

Let us take a closer look at the function of history in *The Aim and Structure*. Duhem's reasoning is frequently illustrated by examples taken from past science; each major claim is supported by historical arguments: representation, natural classification, analogy, etc. Furthermore, two crucial sections of the book are explicitly devoted to history: part one, chapter three: "Representative Theories and the History of Physics" and part two, chapter seven, paragraph six: "The Importance in Physics of the Historical Method". The following passage summarizes nicely Duhem's attitude:

"The legitimate, sure, and fruitful method of preparing a student to receive a physical hypothesis is the historical method. To retrace the transformations through which the empirical matter accrued while the theoretical form was first sketched; to describe the long collaboration by means of which common sense and deductive logic analyzed this matter and modeled that form until one was exactly adapted to the other; that is the best way, surely even the only way, to give to those studying physics a correct and clear view of the very complex and living organization of this science."<sup>38</sup>

##### 5. *On Relative Motion*

One should not omit to consider a further reference in Duhem to Mach. In a series of articles on relative and absolute motion, which Duhem published between 1907 and 1909<sup>39</sup>, he brings up the debate over the principle of inertia and the system of coordinates with respect to which the motion of bodies is to be compared. Duhem was resuming discussion of an issue he had already raised in his review of Mach's *The Science of Mechanics*, and it is best to begin with this text in order to understand his position. Duhem devoted a section to examining in some detail Mach's discussion of "Newton's Views of Time, Space, and Motion". He recalls the critical analysis of absolute space and time given simultaneously by Mach and Carl Neumann<sup>40</sup>. He then brings out the different philosophical attitudes possible with regard to the problem of the choice of a clock and a

system of coordinates: realist immaterialist, realist materialist and positivist. Duhem mentions Neumann's proposal to postulate a body alpha, adding that one need not ascribe a concrete material reality to this body alpha. And he ends by quoting Mach's conclusive remark in response to Emil Budde's suggestion to consider this body as a medium, somewhat like ether: the problem being that we have no physical means to detect the properties of this medium. Now, a difficulty arises in this debate: when Duhem took up the matter again, Mach was revising considerably his presentation; he dropped precisely this remark.

Returning to the issue in his article on absolute and relative motion, Duhem recalls Mach's principle as originally presented in *History and Root of the Principle of the Conservation of Energy* in 1872, according to which the influence of all celestial bodies must be taken into consideration:

“What share has every mass in the determination of direction and velocity in the law of inertia? No definite answer can be given to this by our experiences. We only know that the share of the nearest masses vanishes in comparison with that of the farthest. We would, then, be able completely to make out the facts known to us if, for example, we were to make the simple supposition that all bodies act in the way of determination proportionately to their masses and independently of the distance, or proportionately to the distance, and so on.”<sup>41</sup>

We know that this view, which Albert Einstein was to call Mach's principle, came to play an important role in his theory of general relativity. Retrospectively, one can only be disappointed on discovering that Duhem dismisses Mach's proposal in the following terms:

“This curious hypothesis formulated by Mr. Ernst Mach does not resolve the problem of place and absolute motion. It speaks of velocities and accelerations; it requires us then to inquire into the term, motionless by definition, with respect to which these motions are referred.”<sup>42</sup>

Duhem then goes on to describe in some detail Neumann's body alpha. He gives his preference to this solution, as long as one does not conceive it as a real body. Mach had made it clear that his solution was different from that of Neumann, and accused the later

of merely dressing in new garb the absolutist conception of space and time. His proposal was rather to reformulate the principle of inertia by taking into account all the masses of the universe.

Duhem obviously missed the importance of Mach's principle. His refusal is connected with his own definition of space and time, as he gave it in his scientific works. Thus in his *Traité d'énergétique*, in which he refers his reader to the historical survey mentioned, Duhem states — retaining what he says with respect to motion:

“The absolutely fixed system of coordinates [*triède de référence*] is a purely ideal one, having no existence outside of the mind of the theorist; for theory to accomplish its role, it is enough for us to know how to make [...] the absolutely fixed system of coordinates correspond *approximately* to a certain concrete system of coordinates.”<sup>43</sup>

What is perhaps more interesting is the historical interpretation offered by Duhem. To outline it, Aristotle lies at the origin of discussions on the concept of space or place. He started from a definition of place as the boundary of a body with its surrounding environment. But as this environment could itself be in motion, Aristotle sought for an ultimate term of motion, which he believed could be identified with the earth, supposed to be at rest at the center of the universe. In other words, the term of motion is not a mathematical point but an actual concrete material body. Against this view arose two others. According to Philoponus, a 6<sup>th</sup>-century Christian thinker, inspired by neo-Platonism and stoicism, place is distinct from the bodies that fill it; it is assimilated with a pure three-dimensional space. In consequence, place lacks physical attributes; it is immaterial and has no influence on bodies. This is the absolute space that Newton came to develop for an infinite universe. A third conception, to follow the order given by Duhem, was set forth by Damascius, a neo-Platonic philosopher of the 5<sup>th</sup> century. According to him, place is the set of geometrical measurements making it possible to determine the position of the body. Position is inseparable from the body, which can change position even if no other bodies remain fixed. This does not mean that only relative motions exist, for Damascius admits that the various motions of the universe have a place. But this place concerns neither a real body or abstract space. It corresponds to the best possible disposition of the universe, in other words an ideal state. Historical study reveals the interplay of these fundamental conceptions, as one proceeds from the

finite world to the infinite universe. Duhem does not conceal his preference for Damascius's conception, which he reinterprets with respect to his own scientific views<sup>44</sup>.

Let us add that the historical survey of motion was conceived as part of a larger inquiry on pre-Copernican cosmology that Duhem carried out during the last years of his life, resulting in his ten-volume *Système du monde*<sup>45</sup>. With this major work he established himself as one of the leading historians of science of his time. It is generally acknowledged that he gave the first thorough investigation of medieval science. He explored with a wealth of detail two essential contributions of the Middle Ages: the theory of impetus and the theory of the latitude of forms. The former relating to the motion of bodies, and the latter pertaining to intensive properties and their variations, represented a break with Aristotle and a step toward Galileo. In consequence, the birth of modern science appeared as a continuous, cumulative process. But he also analyzed the fundamental notions of our conceptual scheme — not only motion, but space, time, matter, etc. — as they have changed over centuries. Duhem thus provided a historical backdrop for current debates surrounding these notions. His scientific definitions were grounded on a thorough examination of past conceptions.

To be sure Mach and Duhem developed different accounts of the historical development of science. Mach was ready to take into account some of Duhem's findings concerning the Middle Ages, but not to revise entirely the Enlightenment conception of the scientific revolution, as an event carrying political and social values.

### *Conclusion*

In the preceding pages we went over the evidence for the “far-reaching agreement” between Mach and Duhem. They can be considered as belonging to a broad movement of thought that questions classical mechanicism and causal explanations. They endeavored in common to integrate new branches of physics and to put forth economical description. Mach and Duhem were allied in their fight to promote such views in spite of strong resistance.

They also encouraged their readers to take note of the similarities of their conceptions. The members of the Vienna Circle were attentive to this proximity. Moreover, they combined the complementary analyses of both thinkers, in order to achieve a synthetic view, allowing both for axiomatic development and empirical grounding. As Philipp Frank has it, with regard to Duhem's holism: “One notes how far

Duhem has proceeded on the way from Mach's conception of a physical theory to the conception which was later advocated by logical empiricism"<sup>46</sup>.

We nevertheless encountered some differences between the two philosopher-scientists. Duhem condemned Maxwell's recourse to mechanical models, on the grounds that multiplying differing, discordant models would be an obstacle to the unity of physics. In addition, he refused Mach's principle concerning inertia, because one cannot speak meaningfully of the general order of the universe. But he also showed how economy of thought took on different forms within a precisely delineated analysis of theory structure. Whereas Duhem's highly formal unification of physics within the framework of a general thermodynamics provided a logically penetrating account, Mach's pluralistic methodology was more flexible and receptive to innovations.

Of course, the early reception of Mach and Duhem highlighted certain points to the detriment of others. In particular, the importance ascribed to history of science was in the main neglected. Owing to the evolution of philosophy of science during the past twenty years, we can now appreciate more readily this historical concern. Indeed, Mach and Duhem associated closely rational analysis and historical study. What they asserted thereby is that the way science actually developed is essential for the philosopher. Such a two-fold approach has the advantage of connecting reflections on science with scientific practice.

Furthermore, they already anticipated — more precisely than is generally believed — the perspective of a historical epistemology. At the time Louis Couturat, clearly alluding to Mach, described his view as an "evolutionist epistemology"<sup>47</sup>, and Rey, drawing on both Mach and Duhem coined the expression "historical epistemology"<sup>48</sup> to qualify the method he was promoting. Such a perspective, integrating historical study and conceptual analysis, has come again today to the fore<sup>49</sup>. It is not only of interest to recall its origins, but also to submit to a precise scrutiny early instances of this method, so as to determine, in knowledge of the fact, the role history is to play with regard to philosophy.

## Notes

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<sup>2</sup> Pierre Duhem, “Analyse de l’ouvrage d’Ernst Mach: *La Mécanique*”, in: *Bulletin des sciences mathématiques* 27, Oct. 1903, pp. 261-283. Reproduced in Duhem, *L’Évolution de la mécanique* (1903). Paris: Vrin 1992. English translation Michael Cole, *The Evolution of Mechanics*. Alphen aan den Rijn: Sijthoff & Noordhoff 1980.

<sup>3</sup> Ernst Mach, *Erkenntnis und Irrtum: Skizzen zur Psychologie der Forschung* (1905), in: *Ernst Mach Studienausgabe*, Band 2. Berlin: Xenomoi 2011, pp. 5-6. English translation Thomas J. McCormack, *Knowledge and Error*. Dordrecht: Reidel 1976, p. XXXV. Elisabeth Nemeth and Friedrich Stadler’s introduction to the *Studienausgabe* edition was useful in writing this article.

<sup>4</sup> Klaus Hentschel, “Die Korrespondenz Duhem-Mach: Zur ‘Modellbeladenheit’ von Wissenschaftsgeschichte”, in: *Annals of Science* 45, 1988, pp. 73-91.

<sup>5</sup> Anastasios Brenner, “Les voies du positivisme en France et en Autriche: Poincaré, Duhem et Mach”, *Philosophia Scientiae* 3, 2, 1998, pp. 31-42.

<sup>6</sup> Mach, *Die Mechanik in ihrer Entwicklung: Historisch-Kritisch dargestellt* (1883), in: *Ernst Mach Studienausgabe*, Band 3. Berlin: Xenomoi 2012. French translation Émile Bertrand, *La Mécanique: Exposé historique et critique de son développement* (1904). Paris: Gabay 1987. This edition contains a preface dated July 1903, not published elsewhere. The introduction by Gereon Wolters and Giora Hon to the *Studienausgabe* edition provides helpful information.

<sup>7</sup> Mach, *Populär Wissenschaftlichen Vorlesungen* (1896) in: *Ernst Mach Studienausgabe*, Band 4. Berlin: Xenomoi 2014. English translation Thomas J. McCormack, *Popular Scientific Lectures*. La Salle, Illinois: Open Court 1986.

<sup>8</sup> Duhem, “La tradition de Buridan et la science italienne au XVI<sup>e</sup> siècle”, in: *Bulletin italien*, 10, 3, 1910, pp. 202-231. Reproduced in: Duhem, *Études sur Léonard de Vinci* (1906-1913). Paris: Archives contemporaines, 3 vols, 1984.

<sup>9</sup> Duhem, “Un document relatif à la réforme du calendrier”, in: *Hommage à Louis Olivier*. Paris: Maretheux 1911, pp. 97-103.

<sup>10</sup> Mach, *Die Mechanik*, *op. cit.*, p. 5, translation mine.



- <sup>11</sup> Duhem, *La Science allemande*. Paris: Hermann 1915, p. 122.
- <sup>12</sup> Mach, *La Mécanique*, *op. cit.*, “Préface”, p. 2.
- <sup>13</sup> Mach, *Die Mechanik*, *op. cit.*, p. VI.
- <sup>14</sup> Mach, *op. cit.*, pp. 258-259. This section was added to the 5<sup>th</sup> edition.
- <sup>15</sup> Mach, “Beschreibung und Erklärung” (1906), reproduced in the 1910 4<sup>th</sup> edition of *Populär Wissenschaftlichen Vorlesungen*, *op. cit.*, p. 425.
- <sup>16</sup> Gustav Kirchhoff, *Vorlesungen über mathematische Physik: Mechanik* (1876). Leipzig: Teubner 1877, p. V. Translation mine.
- <sup>17</sup> *Ibid.*
- <sup>18</sup> Duhem had translated Kirchhoff’s “Zur Theorie der Lichtstrahlen” (1882) in: *Annales scientifiques de l’École normale supérieure*, 3, 1986, pp. 303-341. He alluded to Kirchhoff’s conceptions in *L’Évolution de la mécanique*, *op. cit.*, p. 158.
- <sup>19</sup> Duhem, *La théorie physique, son objet et sa structure* (1906). Paris: Vrin, 1981, p. 76; English translation Philip P. Wiener, *The Aim and Structure of Physical Theory*. Princeton: Princeton University Press 1954, p. 53.
- <sup>20</sup> Mach, *Erkenntnis und Irrtum*, *op. cit.*, p. 450. English translation p. 352.
- <sup>21</sup> *Ibid.*, p. 457, English translation p. 357.
- <sup>22</sup> Duhem, *op. cit.*, p. 24; English translation, p. 19.
- <sup>23</sup> Concerning the proximity of Duhem’s views to those of the Vienna Circle, see Brenner, *Les origines françaises de la philosophie des sciences*. Paris: Presses universitaires de France 2003.
- <sup>24</sup> Duhem, *ibid.*, pp. 149-150. English translation, pp. 101-102.
- <sup>25</sup> Mach, *Erkenntnis und Irrtum*, *op. cit.*, p. 178.
- <sup>26</sup> *Ibid.*, p. 179.
- <sup>27</sup> I have analyzed this issue in greater depth in Brenner, *Raison scientifique et valeurs humaines: Essai sur les critères du choix objectif*. Paris: Presses universitaires de France 2011.
- <sup>28</sup> Duhem, *Ibid.*, pp. 25-26 ; English translation, p. 20.
- <sup>29</sup> For a modern assessment of this problem, see Bas van Fraassen, *Scientific Representation*. Oxford: Oxford University Press 2008.
- <sup>30</sup> Mach, *Erkenntnis und Irrtum*, *op. cit.*, p. 388. English translation p. 295-296.

- <sup>31</sup> Duhem, *Les origines de la statique* (1905-1906). Paris: Gabay, 2 vols, 2006. Duhem refers to Mach's *Die Mechanik* in vol. 1, pp. 278-356.
- <sup>32</sup> Mach, *Die Mechanik*, *op. cit.*, p. 75. English translation, p. 77.
- <sup>33</sup> Mach, *Ibid.*, p. 76.
- <sup>34</sup> Mach, *Ibid.*, p. 145.
- <sup>35</sup> Duhem, "De l'accélération produite par une force constant: Notes pour servir à l'histoire de la dynamique", in: Edouard Claparède (Ed.), *Rapports et comptes rendus du deuxième congrès international de philosophie*. Genève: Henry Kündig 1905, pp. 859-915.
- <sup>36</sup> Mach, *Ibid.*, p. 149.
- <sup>37</sup> Duhem, *La théorie physique*, *op. cit.*, p. XV. English translation, p. 3.
- <sup>38</sup> *Ibid.*, pp. 408-409. English translation, pp. 268-269.
- <sup>39</sup> Duhem, "Le mouvement absolu et le mouvement relatif", in: *Revue de philosophie*, 11, 1907, p. 221-235 and 14, 1909, p. 489-508.
- <sup>40</sup> Duhem, "Analyse de l'ouvrage d'Ernst Mach: *La Mécanique*", *op. cit.*, p. 455.
- <sup>41</sup> Mach, *Die Geschichte und die Wurzel des Satzes von der Erhaltung der Arbeit* (1872). Leipzig: Barth 1909. English translation Philip Jourdain, *History and Root of the Principle of the Conservation of Energy*. Chicago: Open Court 1911, pp. 79-80.
- <sup>42</sup> Duhem, *op. cit.*, 13, 1908, p. 649.
- <sup>43</sup> Duhem, *Traité d'énergétique*. Paris: Gauthier-Villars, 2 vols, 1911, vol. 1, p. 13. Authors emphasis; translation mine.
- <sup>44</sup> For a historical survey after the advent of relativity theory, see Max Jammer, *Concepts of Space: The History of Theories of Space in Physics*. Cambridge, Mass.: Harvard University Press 1954. With an illuminating foreword by Einstein.
- <sup>45</sup> Duhem, *Le système du monde*. Paris : Hermann, 10 vols, 1913-1959.
- <sup>46</sup> Philipp Frank, *Modern Science and its Philosophy*. Cambridge: Harvard University Press 1949, p. 16.
- <sup>47</sup> Louis Couturat, "La logique et la philosophie contemporaine", in: *Revue de métaphysique et de morale* 14, 3, 1906, pp. 318-341.
- <sup>48</sup> Abel Rey, *La théorie de la physique chez les physiciens contemporains*. Paris: Alcan 1907, p. 13.

<sup>49</sup> For a recent example, see Matthias Schemmel, *Historical Epistemology of Space: From Primate Cognition to Spacetime Physics*. Vienna: Springer 2016.