

PIERRE DUHEM AND ERNST MACH ON THOUGHT EXPERIMENTS

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The conventional interpretation that Pierre Duhem condemned outright any type of thought experiment in Ernst Mach's sense should be, at least in large part, rejected. Although Duhem placed particular emphasis on the perils of thought experiments that Mach had overlooked or at least underestimated, he retained the core idea of Mach's theory, according to which thought experiments cannot break free from the ultimate authority of real-world experiments. This similarity between Duhem's and Mach's views about thought experiments is not the only one. Just as there was in Duhem's criticism of "expériences fictives" a tendency leading him to give voice to one of Mach's basic empiricist claims, so also there was in Mach's interpretation of thought experiments a tendency in the direction of Duhem's conventionalism. If Mach's and Duhem's conceptions of thought experiments are compared, there results an importantly similar, although not identical, tension that should properly be taken into account in the more general comparison between Mach and Duhem.

1. Introduction

As I have shown in Buzzoni (2018), the conventional interpretation that Pierre Duhem condemned outright any type of thought experiment in Ernst Mach's sense should be, at least in large part, rejected.¹ The conventional reading clashes with the fact that Mach himself, albeit in one very brief remark added to the second edition of *Erkenntnis und Irrtum* (1906), suggested a very different reading

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1. For the conventional interpretation, see, e.g., Yourgrau (1964, 360), Brown (1986, 2), Nersessian (1992, 291), Sorensen (1992, 48–49), Kühne (2005, 203–5), Moue et al. (2006, 65), Asikainen and Hirvonen (2014, 1238), and Brown and Fehige (2016).

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of Duhem's position. According to Mach, Duhem's criticism of thought experiments was perfectly coherent with the fundamental requirement he had stipulated for them, namely, that thought experiments be based on real-world experiments, which are the ultimate criteria of their truth.

This article will take up and develop this interpretation. Section 2 will offer a brief reconstruction of Mach's account of thought experiments. Sections 3 and 4, although essentially restating the results mentioned above, will provide some additional evidence for the claim that Duhem's criticism was only intended to be a completion of and supplement to Mach's theory. As we shall see, the conventional interpretation seems to be in conflict not only with Mach's utterances and silences, but also with what Duhem said and did not say concerning his agreements and disagreements with Mach's account of thought experiments. Thus, I will reinforce the conclusion of the article mentioned above: Duhem retained the core idea of Mach's theory, according to which thought experiments cannot break free from the ultimate authority of real-world experiments, although he placed particular emphasis on the perils of thought experiments that Mach had overlooked or at least underestimated.

Section 5 will expand this interpretation, pointing out a more general similarity between Mach and Duhem. If Mach's and Duhem's conceptions of thought experiments are compared, there results an importantly similar, although not identical, tension that should properly be taken into account in the more general comparison between Mach and Duhem. Just as there was in Duhem's criticism of what he called "expériences fictives" a tendency leading him to give voice to one of Mach's basic empiricist claims, so also there was in Mach's interpretation of thought experiments a tendency in the direction of Duhem's conventionalism, which emphasizes the spontaneity of the human mind and its irreducibility to the data of experience.

2. Mach and the Intrinsic Link between Thought Experiments and Real-World Experiments

Contrary to what was commonly believed until a few decades ago, it was not Mach who introduced the term 'thought experiment' but the Danish scientist Hans-Christian Ørsted (1920); and he did so (not only in Danish [*Tankeexperiment*] but also in German [*Gedankenexperiment*]) with the purpose of clarifying an aspect of mathematics and its relation to physical knowledge in Kant (Witt-Hansen 1976, 53–54). However, the Kantian point of view on thought experiments (and on their relationship to real-world experiments) had no impact on the historical development of the concept. A glance at the history of the phi-

philosophy of science is sufficient to find at least one of the most important reasons for this historical fact: since its beginnings at the end of the nineteenth century, philosophy of science consistently rejected the existence of a priori knowledge in Kant's sense. This occurred either (1) in the empiricist spirit of Mach, neopositivism, and Karl Popper or (2) in the conventionalist spirit of Henri Poincaré and Duhem, later carried on by the relativist philosophy of science of the 1960s and by the "sociological turn," which construed the a priori as changeable and as a function of historically shifting pragmatic interests.

In the case of Mach, this same reason led to the opposite effect. Mach's paper "Über Gedankenexperimente" (1896–97), modified and expanded, was recast in his *Erkenntnis und Irrtum* (1906), and Mach's use of the expression *Gedankenexperiment* spread rapidly with the spread of the knowledge of his philosophy. Mach's idea forced itself on the attention of Franz Brentano's critical notice (see Brentano 1988), which, although it remained at that time unpublished, could have exerted an essential influence on Alexius Meinong's critique of the concept of thought experiments (see Meinong 1907).

An important feature of Mach's account is that he highlights a fundamental similarity between thought and real-world experiments, namely, the "method of variation" (*Methode der Variation*): while in real experiments what is varied are natural circumstances, in thought experiments it is representations that are made to vary in order to see the consequences of these variations (see Mach 1906, 203; 1926/1976, 149).

This similarity between real and thought experiments is intimately connected with the fact that the latter presuppose that some real experiments have already been performed, at least at the level of common sense. As Mach says, the play of imagination can properly start only when physical experience is sufficiently rich (1906, 187–88; 1926/1976, 136–37). From Mach's radical empiricist perspective, thought experiments must draw on a previous stock of experiences that accounts for their validity, as well as for their defects and errors, and he explains how they can produce new knowledge apparently without resorting to experience. In this way, Mach set down what was to become the typical empiricist solution to the fundamental problem of any theory of thought experiments: thought experiments mobilize previously acquired information and skills and thus enlarge our knowledge and significantly contribute to its progress (see Mach 1901, 30; 1901/1919, 29–31; cf. in the same sense Mach 1906, 187–88; 1926/1976, 136–37).

According to the main tendency of Mach's view about the relationship between real-world experiments and thought experiments, real experiments are not only chronologically but also logically prior to thought experiments: chronologically because, to be able to formulate thought experiments, one must

have had real experiences; logically because, when faced with some doubt about the conclusions of a thought experiment, we have to resort to real experiments: “The outcome of a thought experiment, and the surmise that we in our thoughts [*in Gedanken*] link with the varied conditions can be so definite and decisive that the author rightly or wrongly feels able to dispense with any further tests by physical experiment. . . . However, the less certain their outcome, the more strongly thought experiments urge the enquirer to physical experiment as a natural sequel that has to complete and to determine the result” (Mach 1906, 188–89; 1926/1976, 137–38; for a further discussion of this issue, see Buzzoni [2008, esp. chap. 2, sec. 1]).²

Notwithstanding a certain tension in Mach’s conception of the primacy of real over thought experiments, to which I shall return in section 5, there is no doubt that the main pillar of Mach’s theory about thought experiments is that they must not only proceed from experience but also return to it, because experience is the ultimate criterion of all sorts of knowledge, and the warrant for any conclusion based upon a thought experiment can be found only in experience.

3. Mach as Interpreter of Duhem

I return now, after this brief reconstruction of some of the fundamental aspects of Mach’s theory of thought experiment, to Duhem’s criticism of *expériences fictives*. As already mentioned, the conventional reading of this criticism is that Duhem condemned outright Mach’s account of scientific thought experiments. However, a footnote added by Mach to the second edition of *Erkenntnis und Irrtum* seems to be fatal to this interpretation. There, Mach writes, “Duhem (Théorie physique, 331 [Duhem 1914/1954, 201–2]) rightly warns against representing thought experiments [*Gedankenexperimente*] as though they were physical, that is pretending that *postulates* are *facts*” (1906, 188n; 1926/1976, 146n, original italics restored).

This passage is clearly at odds with the traditional reading. In accordance with this reading, one would expect Mach to explain and defend his own account of thought experiments against the criticisms of Duhem. On the contrary, we find that, instead of disputing Duhem’s criticism of the *expériences fictives* contained in *La théorie physique*, Mach quotes it with approval. In this way, he clearly subscribes to an interpretation that is very different from, and indeed opposite to, the stereotype we have seen to be taken for granted and

2. I slightly modified McCormack’s English translation in the preceding quotation.

that is ubiquitous in the literature about thought experiments. If he had interpreted Duhem's criticism of thought experiments as a blanket rejection, he would have certainly disputed it rather than cite it approvingly, implicitly taking them as being little more than a restatement of his own view. Thus, Mach's passage suggests very strongly that Duhem's criticism of thought experiments was, in its essentials, coherent with the fundamental requirement we have seen to be fundamental to Mach's account of thought experiments, namely, that they are based on real-world experiments, which are the ultimate criteria of their truth.

The most obvious way out of this difficulty might lie in regarding Mach's remark as a gross misinterpretation of Duhem's criticism. But even those who do not accept the authority of the principle of charity (e.g., because of the attacks from the experimental psychology of reasoning, according to which human beings are very susceptible to fallacies) are nevertheless obliged to admit that, if we reproach someone for having misunderstood something, we should have grounds for making a similar reproach. However, we have no grounds for making a similar reproach regarding Mach. Therefore, the most obvious way out of this difficulty is of no avail in the measure in which it leaves entirely open the question why Mach fell into such an extraordinary misinterpretation.

Kühne (2005)—one of the very few authors who have seriously looked for a way out of this difficulty—concedes that there is no adequate explanation of Mach's misunderstanding. However, he is prepared to bite the bullet, and, making a virtue of necessity, he interprets the passage in question in the sense that Mach “understood Duhem's criticism correctly *and* accepted it” (Kühne 2005, 204). According to Kühne, Mach withdrew his account of thought experiments, but he said nothing, whether in public or in private life, in order not to become embroiled in a dispute with Duhem, whom Mach thought to be a “comrade in arms for the same cause in the philosophy of science,” that is, for the elimination of metaphysical elements from science (203–4).

It is easy to see that this is not a tenable view. The main problem with this reconstruction is that in Mach's writings there is no evidence that he later distanced himself from his own interpretation of thought experiments. It is certainly true that, as Kühne (2005, 205–6) writes, Mach clearly felt Duhem close to his own positions because of his critique of metaphysics; but Kühne's insistence that Mach found Duhem's criticisms so compelling as to abandon totally his conception of thought experiments appears to be totally ad hoc (in Popper's sense) unless some independent reason can be given for it. If no strong and independent reason can be given for this fact, this reading seems to me extremely implausible, because it only shifts the problem from Mach's improbable misinterpretation to the even more improbable lack of some withdrawal on his part.

The only clue that we get from Kühne in favor of his interpretation is a passage in which Mach replies to Adler's suggestion that, in translating Duhem's *La théorie physique* into German, they could simply leave out its second part (in which, it is to be remembered, Duhem's criticism of thought experiments is contained). In this passage, Mach rejected Adler's advice and said that for the time being he was quite content with the degree of agreement with Duhem, notwithstanding the fact that Duhem was "an admirer of Thomas Aquinas" (Mach 1908/1985, 50; cf. Kühne 2005, 205).

I do not think that this is a tenable view. First, there is no independent evidence in favor of the conjecture that the reference to the second part of Duhem's *La théorie physique* is also a reference to Duhem's brief criticism of *expériences fictives*. On the contrary, there are at least two independent reasons to suppose the opposite. (1) The clear distinction between physics and metaphysics plays an important role in the second part of *La théorie physique*, and it is more probably the case that it is from this general point of view that Mach emphasized his own agreement with Duhem and expressed his decision to include this part in the translation. (2) If Adler had alluded to the special section about thought experiments, it would be strange that Mach should give no hint as to it. Thus, Mach's silence is left unexplained in the same measure as his alleged misinterpretation of Duhem's criticism.

But these are minor points. The main problem with this argument is that it shows the opposite of what Kühne thinks. The fact that Mach thought Duhem to be a "comrade in arms" for the same cause in the philosophy of science not only does not explain Mach's silence on such an important issue but clashes with it, unless we are willing to cast doubt upon Mach's intellectual honesty. If Mach had accepted Duhem's critique of his concept of thought experiments, he should have openly rejected his own theory of thought experiments—and not only in private but still more in public—in order to render his case against metaphysics even more coherent and convincing. The only way to avoid this is to cast doubt upon Mach's intellectual honesty. But we have no reason for doing so. On the contrary, so far as we know, he was immune from flattery (see Hentschel 1988, 86), and we know many cases in which, when confronted with Duhem's objections, he did not hesitate either to recognize his mistakes and change his mind or to reply and record all points of disagreement. Even though Mach sought agreement with Duhem, where it was not reached he provided a fair statement of disagreement.³

3. Even a quick glance at the references to Duhem that Mach added to the subsequent editions of his *Mechanik* is sufficient to attest to this: cf., e.g., Mach (1915), but see also Hentschel (1988, esp. 86–88).

Up to this point, I have assumed without question the most important premise of Kühne's interpretation, that is, that Mach made no further reference at all to Duhem's criticism of thought experiments. But this is probably false. There is a passage in Mach's "Vorwort" to the German translation of *La théorie physique* that suggests disagreement, although not a very serious one, or, more precisely—very much in accordance with the view I am advocating—some divergences in spite of a substantial agreement. Mach (1908, iv) writes, "Duhem regards the model, like the picture, as a parasitic growth. That and where he seems here to go too far, I have explained elsewhere" (my translation).

There is some reason to think that Mach is here alluding to Duhem's objections against thought experiments, given his reference to Duhem's attack on models. As is well known, it is in the context of his criticism of the inductive method that Duhem raised the issue of thought experiments. But Duhem's criticism of the inductive method is intimately connected with an illegitimate employment of imagination in science, which does not tend to construct a scientific "theory" in Duhem's sense, that is, as a "symbolic construction of the human mind" (construction symbolique de l'esprit humain; Duhem 1902, 6–7 [my translation]; but see also Duhem 1914, chap. 2, sec. 1), but only serves the purpose of inventing intuitive hypotheses or models that are not systematically connected with one another (see Duhem [1914], chap. 3, above all sec. 10, where he objects to the English scientists' confusing models with theory).

From this point of view, we may conjecture that, according to Mach, Duhem's objections against thought experiments are in the main correct, even though he seems "to go too far" in rejecting perspicuity and intuitive representation. In fact, Mach ascribes to pictures and intuitive representations a key role in thought experiments, so that we should not be too surprised to find here the most noteworthy divergence from Duhem, concerning this point. This applies to the laws of physics as well as to the geometrical propositions, as Mach pointed out in a passage of the chapter titled "Eine biologisch-teleologische Betrachtung über den Raum" added to the third edition of *The Analysis of Sensations* in 1902:

Scientific geometry set itself the economical task of ascertaining the dependence of quantities on one another, of avoiding superfluous measurements, and of discovering the simplest geometrical facts from which the remaining facts would follow as logical consequences. For this purpose, since we, in our thoughts [*in Gedanken*], do not control nature, but only our own simple logical constructions, our fundamental geometrical experiences had to be conceptually idealized. Now there is no obstacle—by advancing along the road of intuitive representations that are thought of as connected with those idealized experiences—to finding again geo-

metrical propositions in thought experiment [*im Gedankenexperiment*]. The procedure throughout is analogous to that of all the natural sciences. But the fundamental experiences of geometry are reduced to so small a minimum that is only too easy to overlook them altogether. . . . Intuition, physical experiences, and conceptual idealization, are, therefore, the three co-operating factors in scientific geometry. (1902, 144; 1902/1914, 193–94)⁴

In this passage, Mach emphasizes the importance both of visualization, to which the expression “intuitive representation” (*anschauliche Vorstellung*) clearly alludes, and of “conceptual idealization” (*begriffliche Idealisierung*) in thought experiments. Thus, we can see the perhaps most important divergence between Mach and Duhem concerning thought experiments: whereas idealization plays a key role in Duhem’s philosophy of science, the same does not apply to “intuitive representation.”

4. Duhem as Interpreter of Mach’s Account of Thought Experiments

In the preceding section, we saw that what Mach said about Duhem conflicts with the conventional reading of Duhem’s criticism of thought experiments. But we come to the same conclusion if we take into account Duhem’s remarks on this subject.

A general difficulty for the traditional interpretation is that it seems to be in conflict not only with Mach’s utterances and silences but also with what Duhem said and did not say concerning his agreements and disagreements with Mach’s account of thought experiments. In this case, the main difficulty for the traditional interpretation is that it leaves totally unexplained the fact that we cannot find any expression of disagreement concerning Mach’s view about thought experiments in the many passages in which Duhem made reference to Mach.

There is, however, another more specific difficulty with the traditional interpretation. Instead of using the most natural French translation of *Gedankenexperiment*, that is, “*expérimentation mentale*,” Duhem used “*expérience fictive*.” So, the question arises: why did Duhem introduce in 1904 (and reconfirm in 1906) a brand-new phrase for what Mach had called *Gedankenexperiment*, even though he knew that this expression had already been translated into French as “*expérimentation mentale*” (cf. Mach 1901; 1901/1904, 462, 490–91)? It must be remembered that Duhem had known the French translation of Mach’s

4. Here, I have partially modified Williams and Waterlow’s English translation.

Mechanik since 1903—that is, a year before its publication in 1904, when he reviewed it for the *Bulletin des sciences mathématiques* (Duhem 1903).

Both difficulties disappear in the light of the interpretation here defended, according to which Duhem's criticism was probably regarded not only by Mach but also by Duhem himself not as a complete rejection of thought experiments but rather as a completion of and supplement to Mach's theory. It is plain that the first difficulty of the traditional reading does not arise at all in the case of our interpretation. As far as the second is concerned, a plausible answer is to be found in Duhem's review of the French translation of Mach's *Mechanik*, which, besides being entirely consistent with the reading proposed here, also provides an important clue as to why Duhem introduced a new expression. Here, Duhem says of a long quotation from the *Mechanik*—in which Mach exhorts us to imagine nothing beyond “the observable facts”—that “it seems to us that the thoughts here expressed are right and deep” (les pensées qui y sont exprimées nous semblent justes e fortes; Duhem 1903, 278 [my translation]). Here is a part of the quotation:

Pour rester fidèles à la méthode qui a conduit les chercheurs les plus illustres, Galilée, Newton, S. Carnot [Duhem: Sadi-Carnot], Faraday, J.R. [Duhem: J.-R.] Mayer, à leurs grandes découvertes, nous devons limiter notre science physique à l'expression des *faits observables*, sans construire des hypothèses *derrière* ces faits, où plus rien n'existe qui puisse être conçu ou prouvé. Nous avons donc simplement à découvrir les dépendances réelles des mouvements des masses, des variations de la température, des variations de valeur de la fonction potentielle, des variations chimiques, sans nous *imaginer* rien d'autre sous ces éléments, qui sont les caractéristiques physiques directement ou indirectement données par l'observation. (Mach 1901; 1901/1904, 466, last italics added; the points where Duhem's quotation deviates from the published version are enclosed in square brackets)

It is sufficient to mention the important role played by imagination in Duhem's criticism of crucial experiments, in order to get a clue that it is this imaging—and not imagination as the capacity of the mind to counterfactually anticipate what specific answers nature will give to our scientific questions put to nature—that makes Duhem speak of “fictitious experiments” and distinguish these latter from Mach's thought experiments.

According to Duhem, it is impossible to judge trenchantly between two rival hypotheses (to use Duhem's example: between the emission and wave hypotheses concerning light) because they never constitute in physics a strict di-

lemma: “Between two contradictory theorems of geometry there is no room for a third judgment; if one is false, the other is necessarily true. Do two hypotheses in physics ever constitute such a strict dilemma? Shall we ever dare to assert that no other hypothesis is *imaginable* [French: *imaginable*]? Light may be a swarm of projectiles, or it may be a vibratory motion whose waves are propagated in a medium; is it forbidden to be anything else at all?” (Duhem 1914, 311; 1914/1954, 189, italics added).

In view of this, my conjecture is that Duhem wanted to distinguish an illegitimate use of imagination from a legitimate one. For this purpose, he introduced a brand-new phrase for what Mach had called *Gedankenexperiment*, even though he knew that this expression had already been translated into French as the most natural expression “*expérimentation mentale*.” For this purpose, he set beside Mach’s expression, and not against it, that of “*expérience fictive*,” which expresses the rejection of thought experiments that lose connection with experimental practice. “Fictitious experiments” are the product of an illegitimate use of the imagination, namely, the same one that, according to Mach, leads one to assume occult causes beyond phenomena.⁵

We find another point in favor of this conjecture in Mach’s *Mechanik*. Here, an implicit distinction is made between a responsible and a too free use of thought experiments, even though Mach does not make any terminological distinction. With reference to Carl Neumann, Mach writes, “The celebrated mathematician appears to me to have made here too free a use of thought experiment [*Gedankenexperiment*], the fruitfulness and value of which cannot be denied. When experimenting in thought [*im Gedankenexperiment*], it is permissible to modify *unimportant* circumstances in order to bring out new features in a given case. But that the universe is without influence [*Dass aber die Welt einflusslos ist*] is not to be antecedently assumed” (1901, 291; 1901/1919, 572).⁶

Because we know that Duhem reviewed Mach’s *Mechanik*, and in consistency with what has already been said, it seems to me not exceedingly hazardous to say that passages such as the above may have suggested to Duhem the advisability of marking off thought experiments that are dangerous, namely, “fictitious” ones.

To sum up: The conventional interpretation that Duhem condemned outright any type of thought experiment in Mach’s sense is implausible if we consider both Mach’s and Duhem’s claims on this point. If we appeal to their ut-

5. In this connection, it is interesting to note that the German expression “*fingierte Gedankenexperimente*” used by Adler to translate into German Duhem’s “*expériences fictives*” (see Duhem 1906/1908, 269) had already been employed by Mach himself, although in an essentially neutral context (Mach 1901, 32).

6. Here, I have slightly modified McCormack’s English translation.

terances and silences, all the evidence we have sweeps us toward the reading defended here, according to which Duhem's criticism was not intended to be a complete rejection of thought experiments; it was intended to be a completion of and supplement to Mach's theory. Duhem, while retaining the core idea of this theory—according to which thought experiments cannot break free from the ultimate authority of real-world experiments—placed particular emphasis on the perils of thought experiments that Mach had overlooked or at least underestimated. So far as physics is concerned, he mistrusts any anticipation of nature in thoughts that posits unobservable causes inaccessible to experimental practice. This mistrust led him to reserve the term 'fictitious experiments' for forms of thought experiments that are seemingly means for investigating the world but are really pieces of metaphysics in disguise.

The question we have now still to consider is whether such an interpretation stands up to a careful reading of the relevant passages that Duhem devoted to thought experiments. As we shall see, a close reading of Duhem's text seems to support my interpretation.

Duhem recognizes four kinds of "fictitious experiments": the unperformed experiment, the experiment that would not be performed with precision, the absolutely unperformable experiment, and the absurd experiment. The first two are invented only to convince students that some assumptions that are still only hypothetical rest on an experimental basis. Concerning the first of these two kinds of experiment, Duhem writes (using the verb "imaginer" in the negative sense already spoken of) as follows:

Obliged to invoke a principle which has not really been drawn from facts or obtained by induction, and averse, moreover, to offering this principle for what it is, namely, a postulate, the physicist imagines [*imagine*] an experiment which, were it carried out with success, would possibly lead to the principle whose justification is desired. To invoke such a fictitious experiment [*expérience fictive*] is to offer an experiment to be done for an experiment done; this is justifying a principle not by means of facts observed but by means of facts whose existence is predicted, and this prediction has no other foundation than the belief in the principle supported by the alleged experiment. (1914, 331; 1914/1954, 201–2)⁷

The second kind of fictitious experiment goes wrong by yielding results that are too inaccurate to be of any value: "The very indecisive and rough results it would produce could undoubtedly be put into agreement with the proposition

7. Here, I slightly modified Wiener's English translation.

claimed to be warranted; but they would agree just as well with certain very different propositions; the demonstrative value of such an experiment would therefore be very weak and subject to caution. The experiment that Ampère imagined in order to prove that electrodynamic actions proceed according to the inverse square of the distance, but which he did not perform, gives us a striking example of such a fictitious experiment” (Duhem 1914, 331; 1914/1954, 202).⁸

In both cases, there is nothing that Mach would not have accepted. In both cases, it is plain that Duhem does not wish to belittle the value of the formulation of the experimental question but only to denounce the methodological mistake (and perhaps the intellectual dishonesty) of those who try to pass off his wild speculations or too inaccurate and relatively indeterminate results in the guise of facts that have been experimentally ascertained. The methodological mistake does not lie in formulating bold experimental questions; it consists in passing off experiments that were never carried out or that could not be executed with the necessary accuracy as successful ones.

The third kind of fictitious experiment “is not only not realized but incapable of being realized; it presupposes the existence of bodies not encountered in nature and of physical properties which have never been observed” (Duhem 1914, 332; 1914/1954, 202). Again, in this there is nothing that Mach should not have accepted. Duhem does not give an explicit definition of philosophical or metaphysical thought experiments, but what he says here seems to allude to them. He rightly rejects scientific thought experiments that do not have at least an implicit reference to a real experiment. By the way, I think he is right about this. A thought experiment would be devoid of empirical meaning (i.e., it would not be a thought experiment proper to empirical science) if, in formulating and evaluating it, it did not possess, even while it is still in our minds, an intrinsic reference to experience. This is the ultimate reason why all empirical thought experiments must be thought of as translatable into real ones and all real experiments as realizations of thought ones (on this point, see Buzzoni [2008]).

Finally, Duhem discusses the “absurd experiment” (*expérience absurde*)—“a form more illogical than all the others”—which “*claims to prove a proposition which is contradictory if regarded as the statement of an experimental fact*” (1914, 333; 1914/1954, 201, with original italics restored). In this kind of thought experiment, assumptions are made that, although they are presented as facts of experience, it is “contradictory” to conceive of them in this way.

8. Here, I slightly modified Wiener’s English translation.

The interesting question then arises as to how “contradictory” should be understood. Duhem illustrates the absurd fictitious experiment by quoting a passage from Joseph Bertrand’s *Leçons sur la théorie mathématique de l’électricité*. There, Bertrand (1890, 71) argued that “if we accept it as an experimental fact that electricity is carried to the surface of bodies, and as a necessary principle that the action of free electricity on the points of conductors should be null,” we can deduce that electrical attractions and repulsions are inversely proportional to the square of the distance. According to Duhem, however, the proposition that “there is no electricity in the interior of a conducting body when electrical equilibrium is established in it” cannot be regarded as the statement of an experimental fact, since there is no empirical procedure for ascertaining whether there is or is not any electricity in the interior of a conducting body, say, in a piece of copper:

How can we go about establishing whether there is or is not any electricity at this point? It would be necessary to place a testing body there, and to do that it would be necessary to take away beforehand the copper that *is* there, but then this point would no longer be within the mass of copper; it would be outside that mass. We cannot without falling into a logical contradiction take our proposition as a result of observation. . . . We hollow out a cavity in a conducting mass and note that the walls of this cavity are not charged. This observation proves nothing concerning the presence or absence of electricity at points deep within the conducting mass. In order to pass from the experimental law noted to the law stated we play on the word interior. Afraid to base electrostatics on a postulate, we base it on a pun. (Duhem 1914, 333–34; 1914/1954, 203)

Duhem’s argument is not very convincing for many reasons. First, there is an *ignoratio elenchi*. There were many other experiments that showed that all the electricity goes to the surface when a body is electrified, and not only that quoted by Duhem in this passage (cf., e.g., Ganot 1868, 613–14; 1887, 2:1107–8). Second, the experiment mentioned by Duhem can be formulated by means of a passage to the limit, which makes for me (but probably not for Duhem) this empirical (thought) experiment quite convincing: as Duhem says, we may hollow out a cavity in a conducting mass and note that the walls of the cavity are not charged, but we may also repeat the same experiment with cavities (or with spheres, in Biot’s case) that are smaller and smaller in volume, to see if it always yields the same results.

However, in our context, the strength of Duhem’s argument is much less important than its meaning. If we look at the spirit of Duhem’s definition

of absurd thought experiments, we may say that its point is similar to although distinct from that of the preceding kinds of fictitious experiments. To see this, it is important to remember that Duhem's objections against fictitious experiments are set forth in the section titled "Consequences Relative to the Teaching of Physics." Their general purpose is to illustrate that the erroneous principle that each hypothesis of physics may be subjected in isolation to experimental tests leads to false consequences concerning the method by which physics should be taught. According to this principle, physics "would be taught as geometry is: hypotheses would follow one another as theorems follow one another; the experimental test of each assumption would replace the demonstration of each proposition" (Duhem 1914, 329; 1914/1954, 200).

In this connection, Duhem's criticism of the absurd experiments means essentially that we need to clearly distinguish between the propositions of geometry, which are neither to be confirmed nor refuted by experience, and the theories of physics, which are a system of mathematical propositions that aim to represent as simply, as completely, and as exactly as possible a set of experimental laws. This is the sense in which we have to understand the "contradiction" of which Duhem speaks: it is a contradiction to consider some initial hypotheses as logico-mathematical propositions that can neither be proved nor disproved by experience, and at the same time as propositions that express a scientific theory, which must be confronted with experience. Again, there is nothing in Duhem's remarks that explicitly rejects thought experiments in Mach's sense. Just as in the case of the preceding kinds of fictitious thought experiments Duhem, like Mach, only emphasizes that the ultimate authority of thought experiments consists in experience, so also in the case of the "absurd experiments." In all cases, one must keep clearly in mind that thought experiments have their value only as they are based on real experiments or prepare them.

Therefore, we come along three diverse lines to the same result as before. The conventional interpretation seems to be in conflict (1) with Mach's utterances and silences, (2) with what Duhem said and did not say concerning his agreements and disagreements with Mach's account of thought experiments, and (3) with a close reading of the few pages Duhem devoted to the critique of fictitious thought experiments in *La théorie physique*. As a result, we are in a position to say that a fundamental error has been committed in interpreting this author as rejecting thought experiments clearly and completely.

There is, indeed, a difference in emphasis and focus between Mach's and Duhem's account of thought experiments. However, this difference has to be seen against the background of a crucial point of convergence. Duhem adopts a very cautious attitude toward the use of thought experiments in physics, but

what he rejects is not so much the use of thought experiments per se as their improper use, that is, their use independently of real experiments, or still better, he emphasizes the dangers inherent in obliterating the fundamental distinction between real and thought experiments. He accepts in the main the very Machian point that real-world experiments are the ultimate criteria of thought experiments, but a different emphasis is found in Duhem's considerations: worries about the perils involved in thought experiments predominate over the emphasis placed by Mach on their scientific fruitfulness. For this reason, he introduced a new rubric, under which particular thought experiments may be mentioned or discussed: that of "expériences fictives" or—as Adler translated into German—of "fingierte Gedankenexperimente."

A brief comparison between *La théorie physique* and Duhem's earlier article "Quelques réflexions au sujet de la physique expérimentale" (1894) may be helpful in supporting our interpretation from a slightly different point of view. To a very large extent, the content of Duhem (1894) is to be found in an almost verbatim copy in part 2, chapter 6, sections 4–6 of *La théorie physique*, with one exception that is important for our present purpose.⁹ In section 4, Duhem formulates a new objection that is not to be found in his 1894 article. It may be admitted—so the objection goes—that physics, unlike geometry, cannot use the indirect method of reduction to absurdity to obtain the certainty of its conclusions, but the geometer is also acquainted with direct methods of proof, which may be usefully imitated by physics. In order to do that, physical theories could try to derive the hypotheses on which they are based directly from observation, either (1) "by induction or generalisation" or (2) as a corollary that is "mathematically deduced" from experimental laws (Duhem 1914, 313; 1914/1954, 190).

In discussing the first part of this objection—upon which he had briefly touched in the article "Quelques réflexions au sujet des théories physiques" published in 1892 (Duhem 1892, 146–48)—Duhem points out that Newton's principle of universal gravity, because of its "symbolic" and "approximate" character, far from being derivable by generalization or induction from the observational laws of Kepler, formally contradicts them (1914, 317; 1914/1954, 193; Duhem's criticism anticipates that of Popper [1972, 199–201]).

However, in the two sections of Duhem (1914) in which this part of the objection is discussed at greater length, absolutely nothing is said about the second part of it, according to which, in order to imitate geometry, physical the-

9. Thanks to an anonymous reviewer for having hinted at the relevance of this comparison for my purposes.

ories could try to “mathematically” derive the hypotheses on which they are based as corollaries deduced from experimental laws. Hence, the question arises: where is such an answer to be found?

In my opinion, the answer is contained in the immediately following section, “Conséquences relatives à l’enseignement de la physique.” This title is essentially identical to that of the corresponding section of the 1894 article (“Conséquences des principes précédents touchant l’enseignement de la physique”), but this similarity wrongly suggests that the content is the same in both cases. In reality, this section of *La théorie physique* contains Duhem’s criticism of *expériences fictives*, which is the most important addition to the content of the 1894 article, and it is here that one must look for Duhem’s answer to the question already asked: can physical theories “mathematically” derive the hypotheses on which they are based as corollaries deduced from experimental laws? And in fact, as I argued, one of the main targets of Duhem’s criticism of *expériences fictives* is the view that thought experiments may provide physics with a method to imitate geometry. Not Mach’s thought experiments in general but their interpretation as a method of physics that is able to imitate that of direct demonstration in geometry is the proper target of Duhem’s criticism. What Duhem correctly rejects is only a kind of thought experiment that regards its initial hypotheses as having the same epistemological status as logico-mathematical propositions, which do not need either to be proved or disproved by experience, whereas they are freely chosen and experimentally testable only insofar as they are connected with the experimental laws that the theory intends to represent as simply, as completely, and as exactly as possible.

In this sense, a comparison between chapters 4, 5, and 6 of the second part of *La théorie physique* and the 1894 article seems to confirm our interpretation of Duhem’s criticism of *expériences fictives*, according to which this author, while retaining the core idea of Mach’s theory of thought experiments, qualifies and sets limits to it, placing emphasis on perils that Mach had overlooked or at least underestimated.

5. Mach’s and Duhem’s Conception of Thought Experiments: A Common Tension

As we have seen, notwithstanding differences in emphasis—which, among other things, led to a difference in the classification of thought experiments—Duhem’s criticism of “fictitious experiments” was close to Mach’s position and especially to his central claim that the ultimate criteria of thought experiments are real-world experiments. But the similarities between Mach and Duhem con-

cerning thought experiments can also be seen from another angle, by bringing to light a similar, although different, tension or oscillation between their view about the relationship of thought to real-world experiments: similar, because concerning the same two poles, but different, because working in the opposite direction.

This is no place to canvass all points of agreement and points of difference between Mach and Duhem, which would require more specification than I may go into here, but a few general remarks are indispensable for our comparison between Mach's and Duhem's views about thought experiments.

As far as the differences are concerned, I shall confine myself to one difference that many scholars have emphasized and that is of the greatest importance in our context. There is widespread agreement among investigators about the difference between Mach's demand for the reduction of theoretical contents to the "elements" of sensation, that is, to a phenomenalist basis, and Duhem's claim that observations must always be accompanied by a theoretical interpretation in order to be scientifically relevant. What Cassirer—with reference to Duhem—called "transcendence" (*Transzendenz*) of "sensuous experience" (Cassirer 1919, 372–73; 1919/1923, 280) and later on will be called the "theory-ladenness" of observation forms the basis of Duhem's well-known definition of scientific experiment: "An experiment in physics is the precise observation of phenomena accompanied by an *interpretation* of these phenomena; this interpretation substitutes for the concrete data really gathered by observation abstract and symbolic representations which correspond to them by virtue of the theories admitted by the observer" (Duhem 1914, 237; 1914/1954, 147). Moreover, the theory-ladenness of observation is an essential ingredient of Duhem's holistic account of theory testing and of his clear anticipation of Quine's underdetermination of theory choice by empirical evidence.¹⁰

It is not my intention here to deny that these points of Duhem's philosophy of science are at least in tension with Mach's reductionism and epistemological atomism. On the contrary, I admit and maintain that this tension depends on fundamentally different and incompatible assumptions. On this point, Mach's nominalist and reductive instrumentalism, according to which all knowledge

10. Among the briefest and best comparisons between Mach and Duhem that have emphasized these differences are Hentschel (1988, esp. secs. 4–5) and Howard (1990, 364–65). According to Howard, Duhem's holistic thesis is even "simply incompatible with the reductionist and atomistic empiricism in Mach's epistemology." To a certain extent, this was essentially the same point Adler was making when he remarked that Duhem did not consider at all Mach's "elements" of sensation as material foundations of science, and for this reason he was not able to eliminate what Mach had called the "realities that are hidden behind the appearances" (*Realitäten, die hinter den Erscheinungen verborgen sind*; Adler 1908, vi [my translation]). For the comparison between Duhem and Mach, see also Blackmore (1972, 196–97), Pary (1986), and Jaki (1987, 338, 351, 358).

of the world is ultimately resolvable into combinations of “elements” such as colors, sounds, and so forth (cf. Mach 1902, 4; 1902/1914, 5–6), is incompatible with Duhem’s underdeterminationist form of conventionalism, which had been strongly influenced by ideas that, although coming from sources as diverse as Descartes and Pascal, produced a convergent result.

But notwithstanding this, I would like to call attention to some aspects that mitigate, although not eliminate, this opposition between Duhem and Mach and that have an important consequence for the comparison between their accounts of thought experiments. Howard (1990, 365) has maintained that Mach and contemporary Machians minimized the differences and stressed the broad areas of agreement between Duhem and Mach, whereas we find serious and fundamental disagreements between them. But it is precisely for this reason that, insofar as the similarities are concerned, what both Mach and Duhem wrote on this subject is still helpful for avoiding the risk of ending up with a one-sided picture of the relationships between their views. I shall confine myself to a few of the most important points.

I begin with some well-known remarks by Mach on this topic. He says in the preface to the German translation of Duhem’s *La théorie physique* that the elimination of all metaphysics and the principle of the economy of thought is common to both authors (Mach 1908, iii; a similar remark is made by Adler [1908, vi–vii], the translator of Duhem’s work); and in the “Vorwort zur zweiten Auflage” of *Erkenntnis und Irrtum*, to these points of agreement Mach added the fact that Duhem maintained that the only correct method of presenting physical theories is the historical-genetic one (Mach 1906, X; 1926/1976, xxxiii).

A much more detailed list of similarities (and differences) is to be found in Duhem’s “compte rendu” of the French translation of Mach’s *Mechanik*. Duhem calls attention to the following points in common: (1) the principle of economy and more precisely the account both economical and phenomenalist of scientific theories (1903, 264: “Les formules de plus en plus amples et générales de la Physique théorique ne sont que des concentrations, que des résumés abstraits poussés de plus en plus loin”); (2) the freedom of scientists when choosing between different methods of inventing hypotheses (265: “Les procédés d’invention ne se codifient pas”); (3) the holistic nature of experimental tests owing to the presence of the unanalyzed or intuitive ideas (“connaissances instinctives”) that are necessary to carry out experimental tests (265); (4) Mach’s holistic ideas that mechanics cannot be the ultimate basis of all physics and that “tout phénomène appartient à la fois à toutes les branches de la Physique” (279–81); (5) the need for a historical introduction to the principles of scientific theories (267: “La véritable introduction à l’énoncé d’un

principe de Physique est une introduction historique”); (6) the separation of physics and metaphysics (270: “Les fondements de la Mécanique et de la Physique théorique doivent être, aujourd’hui, entièrement indépendants de tout système métaphysique, a fortiori de tout système théologique”); and (7) a certain pluralism in physics, which does not preclude the possibility of attaining a more and more economical science, that is, “une science dont les principes, de plus en plus généraux, nous donnent la représentation résumée d’un ensemble de faits de plus en plus vaste” (281).

Granted the fundamental tension between Mach’s nominalist-reductivist instrumentalism and Duhem’s underdeterminationist form of conventionalism of which we spoke above, the many points of contact between Mach and Duhem (and above all affinities 2, 3, and 4 highlighted by Duhem) raise the question of how to explain them. It seems to me that one explanation, which is in some ways the most plausible that can be given, is that, although proceeding from two diametrically opposite positions, Duhem and Mach were moving toward one another. And the driving force behind this movement was, at least in part, the contrary one-sidedness of their opposing views, which made it necessary for each account to make some significant concessions to the other.

In other words, the theoretical incompatibility between, on the one hand, Mach’s epistemological atomism and phenomenalism and, on the other hand, Duhem’s underdeterminationist form of conventionalism must be recognized; but it does not preclude that there is in both authors a similar, although different, tension or oscillation between opposite views: similar, because concerning the same two poles, but different, because starting from opposite poles and working in the opposite direction. In the effort to overcome the one-sidedness of their alternative starting points, Mach and Duhem sought to converge by introducing qualifications or ideas borrowed from one another, probably driven by the same belief in the value of science, in relation to which they were, as Kühne’s phrase has it, comrades in arms for the same cause.

Let us see, very briefly, how this works in the two cases. In the case of Mach, it is true that the doctrine of theory-ladenness—at least in its most radical form, which includes the last elements of sensation and/or reality—is hard to reconcile with Mach’s phenomenalism, but we must not forget that this latter position, at least from an instrumentalist viewpoint (on which Mach and Duhem to an important extent agree), can be easily combined with a holistic account of theory testing. As Einstein rightly noted in a letter to Schlick of May 21, 1917, “The mental constructions” that “two different peoples pursue physics independently of one another” can be “vastly different,” even though they “agree as regards the impressions (‘elements’ in Mach’s sense)” (quoted in Howard 1990, 370).

Moreover, Mach himself expressed full agreement both with Duhem's claim that experiments would be unintelligible without theory and with his holistic view of theory testing. He writes, "Claude Bernard's advice is to ignore all theory and to leave theory at the door in experimental investigations. Duhem rightly objects that this is impossible in physics, where experiment without theory is unintelligible. . . . In fact, all one can do is to recommend careful assessment whether the experimental result is on the whole compatible with the theory we have assumed [*mitgebrachte Theorie*]. Cf. Duhem (*La Théorie physique*, 297 f.)" (Mach 1906, 202n; 1926/1976, 161n).¹¹ And again: "Duhem (*La Théorie physique*, 364 f.) argues that hypotheses are not so much *chosen* by the enquirers arbitrarily and at will, but rather *obtrude* themselves on the enquirer in the course of historical development, under the impact of facts gradually becoming known. Such a hypothesis usually consists of a whole complex of ideas. If now a result supervenes, for example by an 'experimentum crucis,' that is incompatible with the hypothesis, we can at first regard this result only as contradicting the *whole complex of ideas*. On this latter point cf. Duhem, l.c., pp. 311f." (Mach 1906, 244n; 1926/1976, 184n).¹²

As far as Duhem is concerned, although an underdeterminationist form of conventionalism constitutes the fundamental tendency of his philosophy of science, which has also been historically more influential, there is in Duhem a very different tendency emphasized by some scholars. Lugg (1990, 416), for example, maintained the extreme view that Duhem was not an instrumentalist by emphasizing that Duhem's general strategy is to argue "first that theories are classifications (as opposed to metaphysical explanations) and then to provide considerations for the view that they are more or less natural." And a similar conclusion was reached by Maiocchi (1985, 1990), according to which *La théorie physique* was "a book against conventionalism," and "Duhem regarded most theory choices as decidable on empirical grounds" (Maiocchi 1990, 385).

There is not space in the present article to examine this dispute at the length that it deserves. However, what we have said up to this point is not, at least *prima facie*, compatible with either of these two extreme views. On the contrary, what we have said up to this point seems to indicate that the opposition between the interpreters reflects the fact that in Duhem there are two strains of thought opposing each other. In this sense, the interpretation here proposed supplies some evidence for a more moderate view, which was for example expressed by McMullin (1990, 421) by saying that there is an "ambivalence" in Duhem's thought because he was trying to thread a middle way between two

11. Here, I modified McCormack's English translation.

12. Here, I modified McCormack's English translation.

positions he regarded as extremes: scientific realism and Poincaré's conventionalism. (On this point, see also Paul Needham's contribution, titled "Duhem's Moderate Realism," in Brenner et al. [2010, 7–12].)

But what about the particular case of thought experiments? What is true of Duhem's and Mach's philosophy of science in general is also true of the particular case of thought experiments. In this case, too, we find a similar tension and oscillation. Notwithstanding the incompatibility between, on the one hand, Mach's epistemological atomism and phenomenalism and, on the other hand, Duhem's underdeterminationist form of conventionalism, they generally agreed with each other about the primacy of real over thought experiments and, although proceeding from two diametrically opposite positions, were moving toward one another. More precisely, just as there is in Duhem a tendency leading him to give voice, in his criticism of the *expériences fictives*, to one of Mach's basic empiricist claims, so also there is in Mach's interpretation of thought experiments a tendency in the opposite direction, that is, toward Duhem's conventionalism.

Let us see exactly what this means in the two cases. In the case of Duhem, the main problem is the fact that he did not express an autonomous and developed theory of thought experiments except the one that emerges from his discussion of *expériences fictives*. But even though there are no further explicit indications of Duhem's actual theory about thought experiments, it is easy to see that an inherent ambivalence or ambiguity is contained in his general epistemology. This ambivalence is connected with the fact that, unlike Mach, according to Duhem scientific theories cannot be resolved into mere aggregates of elements or constituents mainly because of the freedom of the human mind in the face of the data of experience. This is an indispensable part of Duhem's conventionalism, without which it cannot be correctly understood and which expresses itself, among other things, in the impossibility of setting any a priori limit on the imagination of the scientist (cf. Duhem 1914, 311; 1914/1954, 189, where there is a passage that I have already quoted in sec. 4) or in its power of making a given fact correspond to an infinity of different formulas or physical laws (Duhem 1914, 275; 1914/1954, 169).

Now, this assumption is inherently ambivalent, and two antithetical solutions were potentially open to Duhem. On the one hand, the freedom or spontaneity of human reason in the face of the data of experience, when combined with an overoptimistic attitude toward its capacities, opened the way to a rationalistic or even Platonist view about thought experiments. If in building theories we are only minimally constrained by empirical data, it is not experience but reason alone that can arbitrate for a thought experiment. At the same time, this same freedom in the matter of theory building, when combined with

the far more cautious attitude of the trained scientist, can make one understandably and justifiably suspicious of thought experiments that break free from the ultimate authority of real-world experiments.

The first path will be followed by Koyré (1939), according to which physics can be done *a priori*. The second one, if our interpretation is sound, will be followed by Duhem, in the way we have been discussing: Duhem, starting essentially from a position that highlights the spontaneity of thought and therefore its irreducibility to experimental data, had to make some significant concessions to Mach's (and Bernard's) empiricism, without which all scientific reasoning would be devoid of any objective value. Hence, Duhem retained the core idea of Mach's theory, according to which thought experiments cannot break free from the ultimate authority of experience, but he placed particular emphasis on the dangers in the use of imagination uncontrolled by experience and real-world experiments.

The tension or oscillation between these two alternatives is much more evident in Mach, albeit, as it were, with inverted sign. As shown by Stäudner (1988) and Buzzoni (2008), there is a strong oscillation, or tension, in Mach's account of the relationship between real and thought experiments. As we said in section 2, the main pillar of Mach's theory about thought experiments is that they must not only proceed from experience but also return to it, because experience is the ultimate criterion of all sorts of knowledge, and the warrant for any conclusion based upon a thought experiment can be found only in experience.

However, although Mach started from a radically empiricist attitude, his interpretation of thought experiments shows a tendency toward Duhem's conventionalism. This tendency is attributable to the fact that, as already shown, he concedes much to Duhem's doctrine of theory-ladenness. Mach's concession leads him to the conclusion that thought experiments come before real experiments, not only in the sense that real-world experiments are the 'natural sequel' of thought experiments because they are their ultimate testing criteria—which is perfectly coherent with Mach's empiricism—but also in the sense of a requirement that agrees with Duhem's conventionalism and clashes with Mach's radical empiricism. A thought experiment not only *de facto* "often precedes and prepares" for a physical experiment; it is also "a necessary *precondition* for physical experiment. Every experimenter and inventor must have the planned arrangement in his head before translating it into fact. . . . Galileo must see the experimental arrangement for investigating free fall well represented in his phantasy before he can realise it" (Mach 1906, 187; 1926/1976, 136–37).

Here, Mach claims that thought experiments are the necessary condition of the possibility of real ones, in the same sense in which the present advocates of

theory-ladenness maintain that a theoretical point of view must necessarily precede observation. Thought experiments, which occur at the hypothetical level, precede real experiments, since observation is always preceded by a thought project: “Deliberate, autonomous extension of experience by physical experiment and systematic observation are thus always guided by thought and cannot be sharply limited and cut off from thought experiment” (Mach 1906, 202; 1926/1976, 149).

Someone might object that according to Mach thought experiments precede real experiments only in a temporal or historico-genetic sense—that is, in the sense of the context of discovery, not in that of justification, or of the appraisal of theories.¹³ Indeed, this is presumably Mach’s point when he writes as follows: “The close conjunction of thought with experience has built modern natural science. Experience produces a thought which is then spun further to be compared again with experience and modified, which produces a new conception, and so on repeatedly” (1906, 200; 1926/1976, 146).

However, Mach does not have this way out for at least two reasons. First, this is not consistent with Mach’s claim, which is contained in one of the passages already quoted (1906, 202; 1926/1976, 149), that real experiments are “always” guided, and thus always preceded, by thought experiments. Second, and more importantly, Mach does not speak of a temporal or historico-genetic “precondition.” Instead, in another of the passages quoted, he speaks of thought experiments as a “necessary” precondition of real experiments (1906, 187; 1926/1976, 136), and necessary (pre)conditions can only be given before or (as Kant’s *a priori* shows) at the same time with, but surely not after, what is conditioned (in this case, real experimentation).

Therefore, the two theses concerning the relationship between thought experiments and real-world experiments—namely, the empiricist subordination of thought experiments to real ones, and the rationalist precedence of the former over the latter—are mutually incompatible. As a result, Mach (as well as Duhem) wavers between the two theses. Just as there was in Duhem a tendency leading him to give voice to one of Mach’s basic empiricist claims, so also there is in Mach—and in particular in his interpretation of thought experiments—a tendency in the direction of Duhem’s rationalism. It is a similar, although different, tension or oscillation between their view about the relationship of thought to real-world experiments: similar, because concerning the same two poles, but different, because working in the opposite direction.

13. A similar objection was made by an anonymous referee.

6. Conclusion

As I have tried to show, the conventional interpretation that Duhem condemned outright any type of thought experiment in Mach's sense should be, at least in large part, rejected. In this article, I took up and developed a different reading, first suggested by Mach, according to whom Duhem, strictly speaking, only insisted that real-world experiments are the ultimate criteria for evaluating scientific thought experiments. Analyzing remarks made both by Mach and Duhem, and taking a second look at the relevant passages in Duhem's *La théorie physique* from a different angle, I maintained that Duhem's criticism of fictitious thought experiments was intended to be a completion of and supplement to Mach's theory. Duhem retained the core idea that thought experiments cannot break free from the ultimate authority of real-world experiments, but he stressed the possible perils of thought experiments—perils that Mach had underestimated, or better still, overlooked.

But the similarities between Mach and Duhem do not end here, as I argued in the last part of this article. If Mach's and Duhem's conceptions of thought experiments are compared, there results a similar, although not identical, tension that should properly be taken into account in the more general comparison between Mach and Duhem. Just as there is in Duhem a tendency leading him to give voice to one of Mach's basic empiricist claims, so also there is in Mach—and in particular in his interpretation of thought experiments—a tendency in the opposite direction, that is, toward Duhem's conventionalism, which highlights the spontaneity of the human mind and its irreducibility to the data of experience. Mach's primacy of thought experiments over real ones does not depend solely on his view that the latter are the ultimate testing criteria of the former but also on a requirement that agrees with Duhem's conventionalism and clashes with Mach's own radical empiricism. The resulting tension in Mach's conception of thought experiments is a further similarity between him and Duhem. It is a different, although similar, tension or oscillation about the relationship of thought to real-world experiments: different, because moving in the opposite direction, but similar, since the two poles of the oscillation are the same.

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