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# History as a Tool for Natural Science: How Ernst Mach Applied Historical Methods to Physics


## ABSTRACT

Historical methods have long been put to use in the making of natural knowledge. In this article, I examine the use of historical methods by nineteenth-century physicists, focusing on the Austrian researcher Ernst Mach in particular. I argue that Mach applied methods characteristic of the then-dominant historical and philological disciplines to his own discipline of physics. He construed history as a tool for the physicist. On the basis of a study of his notebooks and correspondence with the chemist-turned-historian Emil Wohlwill, I explain what he sought to achieve by means of this tool, and reconstruct the practices characterizing his historical research. These practices included the reading, ordering, and comparison of textual sources. Moreover, Mach appropriated the historical-philological method of source criticism. I show that prominent fellow physicists of Mach, including Johann Poggendorff and Hermann von Helmholtz, made use of similar historical methods, even though their aims were different. Together, the cases of these history-writing physicists illustrate how history and natural science continued to intertwine in a time of increasing disciplinary fragmentation.


KEY WORDS: knowledge integration, physicists, historians, the source-critical method, Ernst Mach, Emil Wohlwill, Johann Poggendorff

## INTRODUCTION

The realms of the human and the natural have become inextricably linked due to the massive impact of humans on their environment. One response to this catastrophic development has been to call for a rapprochement of currently

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The following abbreviation is used: DM, Archiv des Deutschen Museums, Munich.

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fragmented studies of the human and natural world. An increasing number of scholars and scientists maintain that only by means of such knowledge integration could researchers face the major problems of the new geological epoch of the "Anthropocene." Historian of knowledge Jürgen Renn, for instance, has argued that current environmental challenges "cannot by subdivided by disciplinary siloes." According to Renn, "the physical science of the Earth system" should be integrated with the "interpretative and critical disciplines of the humanities."[1] Likewise, others have pleaded that "a mix of scientific and humanistic knowledge [is] required to comprehend the Anthropocene in all its complexity."[2] Resonating with these appeals, hybrid fields of inquiry such as climate history, geoanthropology, and environmental humanities have recently been gaining momentum.

While these specific fields and the planetary challenges they confront are relatively new, the intertwining of human and natural knowledge per se is not. Historically, there has been significant overlap between studies of nature and human history in particular. Until circa 1800—that is, before history and natural science were delineated as separate domains of inquiry—historical and natural knowledge self-evidently overlapped.[3] For example, Isaac Newton engaged systematically with chronology and philology, and meteorological data was used in the eighteenth-century genre of universal history.[4] Historical and natural-scientific knowledge-making continued to intersect in the nineteenth century, a period commonly seen as one of specialization and fragmentation. During this period, the study of the history of the Earth and its inhabitants was a multifaceted scholarly enterprise in which conventional boundaries between geology, history, and archaeology were continuously crossed, or simply were not perceived to exist.[5] Twentieth-century examples

1. Jürgen Renn, *The Evolution of Knowledge: Rethinking Science for the Anthropocene* (Princeton, NJ: Princeton University Press, 2020), 8–9.

2. Julia Adeney Thomas, Mark Williams, and Jan Zalasiewicz, *The Anthropocene: A Multidisciplinary Approach* (Cambridge: Polity Press, 2020), chap. 1.

3. Gianna Pomata and Nancy G. Siraisi, eds., *Historia: Empiricism and Erudition in Early Modern Europe* (Cambridge, MA: The MIT Press, 2005).

4. Cornelis J. Schilt, "Of Manuscripts and Men: The Editorial History of Isaac Newton's Chronology and Observations," *Notes and Records* 74, no. 3 (2020): 387–408; Martin Gierl, *Geschichte als präzisierte Wissenschaft: Johann Christoph Gatterer und die Historiographie des 18. Jahrhunderts im ganzen Umfang* (Stuttgart: Frommann-Holzboog, 2012).

5. Pratik Chakrabarti, *Inscriptions of Nature: Geology and the Naturalization of Antiquity* (Baltimore, MD: Johns Hopkins University Press, 2020).

of the overlapping of human history and natural science include collaborations between historians and plant physiologists to date manuscripts, and the incorporation of perspectives from the natural-scientific disciplines by "scientific historians."[6]

Above examples show that the history of the natural sciences is rich in cases in which knowledge and methods normally associated with the study of human history were considered to be relevant for the making of natural knowledge, and vice versa, that historians have sometimes drawn inspiration from the natural sciences. The historical study of these crossovers may help to answer such questions as: In what ways and under what circumstances can history and natural science complement one another? Which tensions arise when knowledge and methods from history and natural science are combined? To reflect on these questions is especially important in a time when (studies of) the human and natural world are again increasingly merged.

This article addresses the use of historical methods by late-nineteenth-century physicists. The focus on physics is perhaps surprising, since this natural-scientific discipline is not evidently historical in focus—unlike, for example, geology, cosmology, or evolutionary biology. Yet, the disciplines of history and physics have stood in a more intimate relationship than one may suspect; historically, the trajectories of history and physics have intersected in consequential ways. It has already been shown that nineteenth- and twentieth-century historians and physicists developed some of their central categories of knowledge—such as the concepts of "fact" and "causality," or the virtues of "objectivity" and "exactitude"—in tandem.[7]

In what follows, I examine the historical intersections of history and physics on the level of practice, demonstrating that historians and physicists have

6. Josephine Musil-Gutsch, "On the Same Page: Paper Technology Practices in the Humanities and the Sciences," *History of Humanities* 5, no. 2 (2020): 355–381; Elena Aronova, *Scientific History: Experiments in History and Politics from the Bolshevik Revolution to the End of the Cold War* (Chicago: The University of Chicago Press, 2021).

7. Sjang L. ten Hagen, "How 'Facts' Shaped Modern Disciplines: The Fluid Concept of Fact and the Common Origins of German Physics and Historiography," *Historical Studies in the Natural Sciences* 49, no. 3 (2019): 300–37; Michael Heidelberger, "From Mill via von Kries to Max Weber: Causality, Explanation, and Understanding," in *Historical Perspectives on Erklären and Verstehen*, ed. Uljana Feest (Dordrecht: Springer, 2010), 241–65; Peter Novick, *That Noble Dream: The "Objectivity" Question and the American Historical Profession* (Cambridge: Cambridge University Press, 1988), 135–41; Sjang L. ten Hagen, "History and Physics Entangled: Disciplinary Intersections in the Long Nineteenth Century" (Amsterdam: University of Amsterdam, 2021), 115–97.

shared not only concepts and virtues but also research methods. More specifically, I explore how historical and natural-scientific methods overlapped in the work of the Austrian physicist Ernst Mach (1838–1916). I argue that Mach sought to establish methods drawn from the historical discipline as an integral part of physics; he fashioned them as a tool for the natural scientist.

Mach's historical studies became internationally renowned and had a major impact on twentieth-century physics. His historical analysis of Newtonian mechanics, which famously debunked notions of absolute time and space, were particularly influential. Most notably, Mach's historical work inspired Albert Einstein on his road to special and general relativity.[8] After Mach died, in 1916, Einstein celebrated his colleague's historical writings as having exerted "tremendous impact upon our generation of natural scientists."[9] Mach's historical writings also exerted a major influence on twentieth-century philosophy,[10] and functioned as an important reference for the first generations of professional historians of science.[11]

Considering their profound impact on twentieth-century science and scholarship, it is hardly surprising that Mach's historical studies have already received considerable scholarly attention.[12] However, previous accounts of Mach's historical work have fallen short in at least one crucial respect: there exist no studies of *how* Mach wrote history. Thus, it has remained unclear what historical methods he employed; how did history and natural science concretely intertwine in his work? As a consequence, it has also remained unclear

8. See, e.g., Richard Staley, "Mother's Milk, and More: On the Role of Ernst Mach's Relational Physics in the Development of Einstein's Theory of Relativity," in *Interpreting Mach*, ed. John Preston (Cambridge: Cambridge University Press, 2021), 28–47.

9. Albert Einstein, "Ernst Mach," in *The Berlin Years: Writings, 1914–1917 (English Translation Supplement)*, vol. 6 of *The Collected Papers of Albert Einstein*, ed. A. J. Kox, Martin J. Klein, and Robert Schulmann (Princeton, NJ: Princeton University Press, 1997), 141–45, on 141.

10. See, e.g., Michael Stöltzner, "Narratives Divided: The Austrian and the German Mach," in *Interpreting Mach*, ed. John Preston (Cambridge: Cambridge University Press, 2021), 208–34.

11. H. Floris Cohen, *The Scientific Revolution: A Historiographical Inquiry* (Chicago: The University of Chicago Press, 1994), 39–45.

12. The most recent and valuable study of Mach as historian is Elisabeth Nemeth, "Zur 'historisch-kritischen Methode' bei Ernst Mach," in *Ernst Mach—Zu Leben, Werk und Wirkung*, ed. Friedrich Stadler (Cham: Springer, 2019), 21–43. Previous studies include: Otto Blüh, "Ernst Mach as an Historian of Physics," *Centaurus* 13, no. 1 (1969): 62–84; Erwin N. Hiebert, "Mach's Philosophical Use of the History of Science," in *Historical and Philosophical Perspectives of Science*, ed. Robert H. Stuewer (Minneapolis: University of Minnesota Press, 1970), 184–203; M. Norton Wise, "On the Relation of Physical Science to History in Late Nineteenth-Century Germany," in *Functions and Uses of Disciplinary Histories*, ed. Loren Graham, Wolf Lepenies, and Peter Weingart (Dordrecht: Springer, 1983), 3–34, on 19–22.

if Mach conformed to the norms of established nineteenth-century historical scholarship. The present article aims to resolve both issues at once by reconstructing the research practices that characterized Mach's historiography[13] and by showing that these mirrored those of nineteenth-century historians.

To uncover Mach's historical aims and methods, I draw from a variety of sources. To begin, I rely on various revised editions of Mach's best-known historical publication, *The Development of Mechanics* (seven editions appeared between 1883 and 1912).[14] I also pay close attention to one of his earliest historical studies, the 1871 lecture *The History and Root of the Principle of the Conservation of Work* (published in 1872).[15] Next to Mach's published historical work, I consult yet largely unexplored archival materials. These include Mach's lecture notes and notebooks. From the early 1870s until 1910, Mach kept fifty-three notebooks of some hundreds of pages each, which provide valuable insight into how his historical research intertwined with his physics (see figure 1). I also draw from Mach's rich and longstanding correspondence with the chemist-turned-historian Emil Wohlwill (1835–1912). The thorough historical studies of Wohlwill were an important reference for Mach. The considerably revised seventh edition of *The Development of Mechanics* (1912) was even dedicated to Wohlwill, whom Mach portrayed as a "highly esteemed historian of physics."[16] Yet, the fruitful intellectual relationship between Mach and Wohlwill has received scant attention from scholars.[17] I argue that, by interacting with Wohlwill, Mach conformed to disciplinary norms and

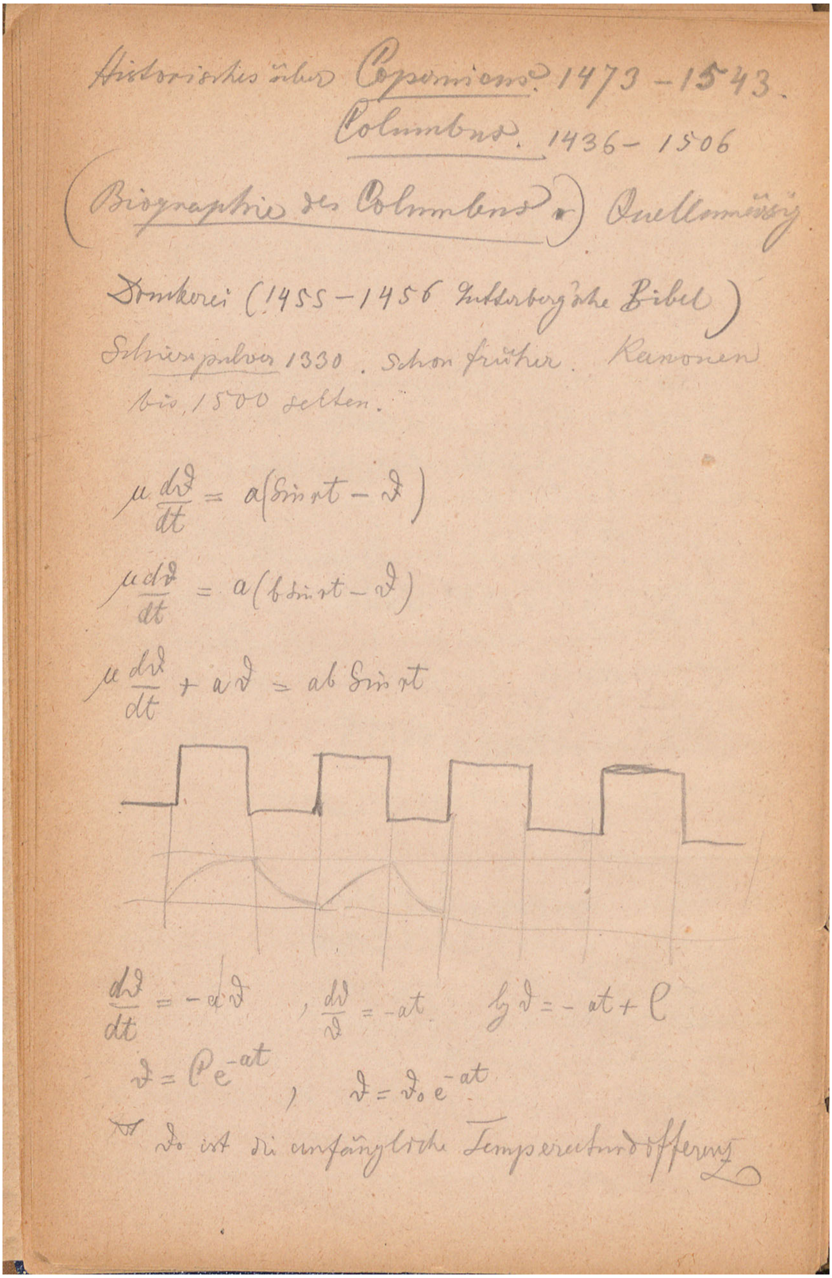
13. I use the term "historiography" instead of "history" when it is important to distinguish between, on the one hand, the writing or discipline of history and, on the other hand, its object or product.

14. Ernst Mach, *The Science of Mechanics: A Critical and Historical Account of Its Development*, trans. Thomas J. McCormack (LaSalle, IL: Open Court, 1960); Ernst Mach, *Die Mechanik in ihrer Entwickelung: Historisch-kritisch dargestellt*, 1st edition (Leipzig: F. A. Brockhaus, 1883). The title of Mach's book is commonly translated as *The Science of Mechanics*. I follow Lydia Patton's suggestion to use of *The Development of Mechanics* as an alternative, more apt translation. See Lydia Patton, "Abstraction, Pragmatism, and History in Mach's Economy of Science," in *Interpreting Mach*, ed. John Preston (Cambridge: Cambridge University Press, 2021), 142–63, on 147.

15. Ernst Mach, *The History and Root of the Principle of the Conservation of Energy*, trans. Philip E. B. Jourdain (Chicago: Open Court, 1911); Ernst Mach, *Die Geschichte und die Wurzel des Satzes von der Erhaltung der Arbeit* (Prague: Calve, 1872).

16. Ernst Mach, *Die Mechanik in ihrer Entwickelung: Historisch-Kritisch Dargestellt,* 7th edition (Leipzig: F.A. Brockhaus, 1912), iii. Translations from German sources to English are mine, unless indicated otherwise.

17. But it has recently been touched upon in Nemeth, "zur 'historisch-kritischen Methode'" (ref. 12), 28–29.


Historisches über Copernicus 1473–1543.
Columbus. 1436–1506
(Biographie des Columbus) Quellenmässig
Druckerei (1455–1456 Guttenberg'sche Bibel)
Schiesspulver 1330. schon früher. Kanonen bis 1500 selten.

$$\mu \frac{d\vartheta}{dt} = a(\sin \nu t - \vartheta)$$

$$\mu \frac{d\vartheta}{dt} = a(b \sin \nu t - \vartheta)$$

$$\mu \frac{d\vartheta}{dt} + a\vartheta = ab \sin \nu t$$

$$\frac{d\vartheta}{dt} = -a\vartheta, \quad \frac{d\vartheta}{\vartheta} = -at, \quad \lg \vartheta = -at + C$$

$$\vartheta = C e^{-at}, \quad \vartheta = \vartheta_0 e^{-at}$$

$\vartheta_0$ ist die anfängliche Temperaturdifferenz

**FIGURE 1.** A one-page excerpt from a notebook kept by Mach during the 1870s. It symbolizes how, in Mach's work, physics and historiography intertwined. The top half of the page contains notes on Columbus and Copernicus, as well as on the invention of printing (*Druckerei*) and gun powder (*Schiesspulver*). On the bottom half of the page are written a set of differential equations and their solutions. *Source:* NL 174/505, DM.

practices of historians. Through their interactions, Mach and Wohlwill connected two disciplines that, by and large, were diverging.

The structure of this article is as follows: I first explain why Mach believed in the unity of historical and natural-scientific knowledge, and why he found that physics in particular would benefit from the incorporation of historical research methods. After that, I reconstruct Mach's own historical methods, and compare them to the methods used by nineteenth-century historians, as well as to those of a number of other physicists writing history, including Hermann von Helmholtz (1821–1894) and Johann Christian Poggendorff (1796–1877). On the basis of these comparisons, I situate Mach's application of historical methods to physics within and between the disciplinary contexts of history and physics. Finally, I discuss what the efforts of these nineteenth-century, history-writing physicists reveal about the relationship between history and natural science more generally.

## THE UNITY OF KNOWLEDGE

Mach was trained as a physicist and built a professional career in physics. But simultaneously, he tried to stretch, cross, and circumvent the boundaries of his discipline.[18] He did so because he was convinced that all knowledge disciplines were principally interconnected: "fixed, sharp lines of demarcation cannot be drawn."[19] For one thing, Mach was a proponent of psychophysics; he held that "the theories and techniques of several disciplines needed to be combined in order to fruitfully study sensory perception."[20] Thus, he claimed that "physics, physiology and psychology stay in an indestructible relationship, so that for each of these [disciplines] salvation can only be found in cooperation with the other ones."[21] Mach also deemed it essential that physicists conducted

18. Richard Staley, "'Beyond the Conventional Boundaries of Physics': On Relating Ernst Mach's Philosophy to His Teaching and Research in the 1870s and 1880s," in *Integrated History and Philosophy of Science: Problems, Perspectives, and Case Studies*, ed. Friedrich Stadler (Cham: Springer, 2017), 69–80.

19. Ernst Mach, "The Economical Nature of Physical Inquiry," in *Popular Scientific Lectures*, trans. Thomas J. McCormack (Chicago: Open Court, 1895), 186–213, on 189.

20. Alexandra Hui, *The Psychophysical Ear: Musical Experiments, Experimental Sounds, 1840–1910* (Cambridge, MA: MIT Press, 2013), xvi.

21. Ernst Mach, "Vorträge über Psychophysik," *Oesterreichische Zeitschrift für praktische Heilkunde* 9 (1863): 362–66, on 365; quoted and translated in Richard Staley, "Sensory Studies, or When Physics Was Psychophysics: Ernst Mach and Physics between Physiology and Psychology, 1860–71," *History of Science* 59, no. 1 (2018): 6. https://doi.org/10.1177/0073275318784104

historical research. He insisted that in physics "historical studies are not so generally cultivated as they should be."[22]

Mach's attempts at knowledge integration extended beyond the connection of individual disciplines like history, physics, and psychology; he sought to reunify the "*Wissenschaften*"[23] at large. In late-nineteenth-century German-speaking contexts, the academic disciplines were increasingly subdivided into two areas: the humanities (*humanistische Wissenschaften* or *Geisteswissenschaften*) and the natural sciences (*Naturwissenschaften*).[24] Mach felt highly uncomfortable with this distinction, stating in an 1866 public lecture, "It has surely often struck you as strange that the [*Wissenschaften*] are divided into two great groups, that the so-called [*humanistische Wissenschaften*] ... are placed in almost a hostile attitude to the [*Naturwissenschaften*]." He rejected that divide: "I must confess that I do not overmuch believe in this partition of the [*Wissenschaften*] ... I believe that both [*Wissenschaften*] are simply parts of the same [*Wissenschaft*], which have begun at different ends." According to Mach, any object of study in the natural sciences also belonged to the humanities, and vice versa: "We come to the understanding of much within us solely by directing our glance without, and vice versa. Every object belongs to both [*Wissenschaften*]." For example, "Church and State are objects of the historian's research, but not less phenomena of nature."[25]

The examples of Church and State provided by Mach suggest that his emphasis on the unity of knowledge was first motivated by his challenge of religious and political absolutes, his main issue being the dogmas of the Catholic church.[26] Second, Mach's commitment to psychophysical research, which concerned *Geist* as much as *Natur*, convinced him that no strict divide should be drawn within the *Wissenschaften*.

A third context in which Mach expressed his belief in the unity of knowledge was pedagogical. Generally, German-speaking scholars and scientists

22. Mach, *History and Root* (ref. 15), 16.

23. It is important to bear in mind that the German term *Wissenschaft(en)*, unlike its English counterpart "science(s)," comprises not only the social and natural sciences, but also the humanities.

24. On the emergence of this distinction, see Jeroen Bouterse and Bart Karstens, "A Diversity of Divisions: Tracing the History of the Demarcation between the Sciences and the Humanities," *Isis* 106, no. 2 (2015): 341–52.

25. Ernst Mach, "Why Has Man Two Eyes?" in *Popular Scientific Lectures*, trans. Thomas J. McCormack (Chicago: Open Court, 1895), 66–88, on 86–88.

26. Deborah R. Coen, *Vienna in the Age of Uncertainty: Science, Liberalism, and Private Life* (Chicago: The University of Chicago Press, 2008), 123.

reflecting on disciplinary unity and disunity in the late nineteenth century, Mach included, did so while seeking to contribute to discussions on the reform of the *Gymnasium*. The *Gymnasium* was the only type of secondary school enabling its graduates to go to university. Traditionally, the curriculum of the *Gymnasium* revolved mainly around classical philology. But starting from the 1820s, those who had recently started to identify as natural scientists attempted to reform the *Gymnasium* to include natural-scientific subjects in its curriculum. By the 1840s, fierce debates had emerged between, on the one hand, those adhering to the predominance of classical philology and, on the other, reformers oriented on the natural sciences. Participants in these debates felt the need to outline the differences between the different knowledge subjects they represented, even if many of them adhered to the ideal that the disciplines, despite their differences, were essentially unified.[27]

Mach also participated in these long-lasting educational debates—he even became co-editor of the Austrian journal *Zeitschrift für den physikalischen und chemischen Unterricht*, which was founded in 1887 and whose key subject was the instruction of the natural sciences at the *Gymnasium*.[28] In contrast to many participating in the discussion, however, Mach emphasized the similarities rather than the differences between the culturally and naturally oriented knowledge subjects. Indeed, he would always stress the complementarity of philological and natural-scientific training; he sought to accommodate and integrate humanistic and natural-scientific modes of learning. More specifically, he pleaded for the implementation of "general education" (*allgemeine Bildung*) in the German-speaking secondary school system.[29] In Mach's concrete outline of such education, history played a central role. He maintained that instead of obliging the youth to scrutinize Ancient texts according to classical philological tradition, as had long been common at the *Gymnasium*, genuinely humanistic instruction should principally awaken their general historical consciousness. In his lecture on the conservation of work, Mach posited that "the essence of classical education is historical education . . . we have a much too narrow idea of classical education. Not the Greeks alone concern

27. Denise Phillips, "Epistemological Distinctions and Cultural Politics: Educational Reform and the Naturwissenschaft/Geisteswissenschaft Distinction in Nineteenth-Century Germany," in *Historical Perspectives on Erklären and Verstehen*, ed. Uljana Feest (Dordrecht: Springer, 2010), 15–35.

28. Coen, *Vienna in the Age of Uncertainty* (ref. 26), 123.

29. Ernst Mach, "On Instruction in the Classics and the Sciences," in *Popular Scientific Lectures*, trans. Thomas J. McCormack (Chicago: Open Court, 1895), 259–95.

us, but all the cultured people of the past." Mach had as little patience with the narrow-minded classicist as with the historically uninformed naturalist. Thus, he added that "there is, for the investigator of nature, a special classical education which consists in the knowledge of the historical development of his [*Wissenschaft*]."[30]

So, Mach believed that all knowledge disciplines were principally interconnected, and pointed to history as providing one connecting thread across them. He developed and propagated these views especially in the context of debates about the German secondary school system. To comprehend why Mach insisted on the essential value of historical research for natural science, one has to understand why Mach believed that all natural-scientific knowledge is inherently historical.

## HISTORICAL STUDY TO ENLIGHTEN PHYSICS

At the start of his 1871 lecture on the history of principle of the conservation of work, Mach cautioned his audience of fellow physicists to "not let go the guiding hand of history." He urged them to embrace the study of history. This was necessary, according to Mach, as "history has made all [and] history can alter all. Let us expect from history all."[31] How had he reached this conclusion that everything, including physics, was made by history? And what did the physicist Mach hope to achieve by means of historical study?

### How Mach's Historical Interest Emerged

The 1860s were decisive for the development of Mach's views. During that decade, Mach was primarily occupied with conducting experiments at the fluid disciplinary borders of physics, psychology, and physiology. For example, he carried out psychophysical experiments related to reaction time and the bodily experience of rotation and fall.[32] Mach's historical interest emerged in the context of such psychophysical investigations, particularly from conversations with the Viennese music critic and theorist Eduard Kulke (1831–1897).

Kulke, like Mach, was interested in both cultural history and natural science. Historian of science Alexandra Hui has pointed out that Kulke and

30. Mach, *History and Root* (ref. 15), 18.

31. Ibid., 18.

32. On these experiments, see Staley, "Sensory Studies" (ref. 21).

Mach drew much inspiration from each other's work: while Kulke was seeking to develop a theory of musical aesthetics "that legitimized both the objective analyses of acoustics and music theory and the subjective experiences of the individual," Mach was engaged in an experimental search for the accommodation mechanism of hearing.[33] Among other issues, Mach and Kulke discussed the differences between the melodies in the music of Slavic and Germanic peoples. They concluded that these differences had no physiological basis but had grown historically. According to Hui, it was through such discussions and because of his failure to find a physiological basis of accommodation in hearing that, in the early 1860s, Mach came to believe "that hearing—how one heard, what one heard, what one focused his or her attention to—was bound to culture and therefore specific to time and place. How one heard could and did change over time. *Hearing itself* was historical."[34]

These insights prompted Mach to study the historical development of musical concepts like consonance and dissonance.[35] Meanwhile, he inferred that if what one heard depended on historical conditions, other forms of experience were probably historical as well. By the early 1870s, Mach had come to understand any form of experience, including sound perception as well as visual observation, as inextricably linked to historical circumstance. He had used the insight that hearing was historical "to show that knowledge itself was historical," as Hui has put it.[36] Thus, Mach concluded that the concepts and laws of physics, as well, had been shaped by history.

## The Relevance of Historiography for Physics

During the winter of 1874–75, Mach scribbled in his notebook that "any justification needs to be historical. The path along which something has been found is also suited for retrieval. What has been found should never be taken as

33. The perceptual phenomenon of accommodation in hearing concerns the influence of someone's deliberate attention on what one hears. For example, the sound of a piano chord varies depending on which of its notes a listener directs their attention. Hui, *The Psychophysical Ear* (ref. 20), 90.

34. Ibid., 93.

35. Ernst Mach, "Uebersicht über die historische Auffassung von Consonanz und Dissonanz" (n.d.), NL 174/4163, DM. In 1864, he gave a lecture on a similar topic: Ernst Mach, "On the Causes of Harmony," in *Popular Scientific Lectures*, trans. Thomas J. McCormack (Chicago: Open Court, 1895), 32–47.

36. Alexandra Hui, "Changeable Ears: Ernst Mach's and Max Planck's Studies of Accommodation in Hearing," *Osiris* 28, no. 1 (2013): 119–45, on 145.

self-evident. The arbitrary should never be presented as absolute. Where there are several paths, they must be shown."[37] This comment illustrates that, according to Mach, the general relevance of historiography lay in its capacity to expose the historicity and contingency of physical concepts, laws, and theories that were normally taken as absolutes. To clarify the liberating potential of historical study for his discipline, Mach drew a parallel between physics and society. He explained he had always struggled to understand "how people could like letting themselves be ruled by a king even for a minute [, and] that wealthy folk upon our sphere, alone possess the riches."[38] He saw two options of approaching these societal issues: "Either one grows accustomed to the puzzles and they trouble one no more, or one learns to understand them by the help of history and to consider them calmly from that point of view."[39] According to Mach, such puzzles related to present-day physics should be approached similarly historically: "Here too there is only one way to enlightenment: historical studies."[40] So, by means of historical study, Mach sought to question the status quo in physics. He maintained that to really understand (and, if necessary, change or replace) currently prevailing theories in physics, one had to study their historical origin and development.

Mach underlined the relevance of historical study for physics on many other occasions. In the lecture notes of a university course for physics students from 1872, he wrote: "If one wishes to understand the meaning of something, one first has to look at its history."[41] A decade later, in the introduction of *The Development of Mechanics,* Mach explained that to "lay bare the core" of the concepts and theories of mechanics, one had to understand their historical development:

> The core of the ideas of mechanics has generally arisen out of the investigation of very simple and special cases of mechanical processes. The historical analysis of the knowledge of these cases remains the most effective and natural method for laying bare this core. Indeed, one can say that real comprehension of the general results of mechanics can only be gained in this way.[42]

37. Ernst Mach, "Notizbuch," 18 Sep 1874, NL 174/509, DM.
38. Mach, *History and Root* (ref. 15), 15.
39. Ibid., 15–16.
40. Ibid., 16.
41. Ernst Mach, "Ueber einige Hauptfragen der Physik," 1872, NL 174/0449, DM.
42. Mach, *Mechanik* (7th ed.) (ref. 16), v.

So, Mach believed that physical concepts, laws, and theories—such as those of mechanics, optics, or thermodynamics—should be studied historically in order to be properly understood, or, to use his own phrasing, to "lay bare their core."

The meaning of this phrase becomes more comprehensible when judged from the standpoint of Mach's epistemology.[43] Mach's epistemology was heavily indebted to how the generation of German-speaking physicists before him had defined their discipline, in the beginning of the nineteenth century. They had systematically distinguished between "facts" and "theories," and so did Mach. He regarded facts—which he defined as complex combinations of so-called "elements" (which in turn he interpreted as "individualized events embedded in real causal-functional relations to one another"[44])—to constitute reality, unlike theories, which he considered as useful but fallible and short-lived descriptions of facts. This is not to say that he considered theorizing unimportant. The crucial function of theory, according to Mach, was to make abstractions of facts as to express, remember, and communicate them in the most simple and convenient, preferably mathematical, form. This he called "economical" description. Any alternative form of theorizing he considered to be unacceptable.

According to Mach, all theoretical descriptions, even the most economical ones, were inevitably incomplete. This was due to the nature of the facts they described. Any fact, Mach insisted, was too "complex" to be fully described by theory.[45] In Mach's words: "A rule, reached by the observation of facts, cannot possibly embrace the entire fact, in all its infinite wealth, in all its inexhaustible manifoldness; on the contrary, it can furnish only a rough outline of the fact, one-sidedly emphasizing the feature that is of importance for the given . . . aim in view."[46] This is why Mach believed that the precise forms of concepts, laws, and theories were shaped by the historical circumstances in which they had been developed.[47] For Mach, this implied that any theory, although useful, was historically contingent. As he put it himself, recapitulating the insight that

43. For nuanced accounts of Mach's epistemology: Erik C. Banks, *Ernst Mach's World Elements: A Study in Natural Philosophy* (Dordrecht: Springer, 2003); Patton, "Abstraction, Pragmatism, and History" (ref. 14).

44. Erik C. Banks, *The Realistic Empiricism of Mach, James, and Russell: Neutral Monism Reconceived* (Cambridge: Cambridge University Press, 2014), 5.

45. Elske de Waal and Sjang L. ten Hagen, "The Concept of Fact in German Physics around 1900: A Comparison between Mach and Einstein," *Physics in Perspective* 22, no. 2 (2020): 55–80, on 62–64.

46. Mach, *Mechanics* (ref. 14), 90.

47. Ernst Mach, *Principles of the Theory of Heat*, trans. Brian McGuinness (Dordrecht: Reidel, 1986), 415.

he had first gained in the context of his acoustic psychophysical research in the 1860s: "What aspects of a fact are taken notice of[] will . . . depend upon circumstances."[48]

By means of historical analysis, Mach aimed to determine under what historical circumstances currently predominant concepts, laws, and theories had formed. Such analysis enabled him to lay bare their factual "core," or to expose their lack of it. Assuming his economical principle, Mach believed that "enlightenment" in physics could be attained by simplifying or replacing physical concepts and theories that had taken unwarrantedly metaphysical or speculative forms in the past. Indeed, he understood it to be the task of the history-writing physicist to find out if and when their predecessors had either followed or left the path of economical description. Such reconstruction he deemed highly important since he was convinced that "one can never lose one's footing, or come into collision with facts, if one always keeps in view the path by which one has come."[49] If Mach judged that one of his predecessors had lost connection to the facts, he would intervene by suggesting an alternative, more economical path that could be explored in the future.

Among the physicists challenged by Mach was Hermann von Helmholtz. Mach's historically informed criticism of Helmholtz's mechanical formulation of the principle of the conservation of work further clarifies how Mach combined historical and conceptual analysis, and what he sought to achieve by it.[50]

In 1847, Helmholtz had formulated the principle of the conservation of work within the framework of Newtonian mechanics. Some quarter of a century later, in his 1871 lecture devoted to this topic, Mach sought to dismantle this link. After arguing that the principle of work conservation was equivalent to the principle of the impossibility of perpetual motion, he claimed that it had been employed long before Newton arrived on the scene. On the basis of a close reading of sixteenth- and seventeenth-century sources (I will elaborate on Mach's reading practices in the next section), he asserted that "since the time of [Stevin] and Galileo, it has served as the foundation of the most important extensions of the physical sciences." Therefore, "this theorem by no means stands and falls with the mechanical view of the world."[51]

48. Mach, *Mechanics* (ref. 14), 90.

49. Mach, *History and Root* (ref. 15), 17.

50. On the content and context of Mach's lecture: Staley, "Sensory Studies" (ref. 21), 21–24; Daan Wegener, "Meaningful Work: Ernst Mach on Energy Conservation," in *Interpreting Mach*, ed. John Preston (Cambridge: Cambridge University Press, 2021), 48–66.

51. Mach, *History and Root* (ref. 15), 20.

Subsequently, Mach more fundamentally criticized the Newtonian mechanical worldview, which was celebrated by Helmholtz and many other physicists in the late nineteenth century. He argued that to suppose the equivalence of heat and electricity as similar forms of mechanical movement, as the proponents of the mechanical view of nature did, was to move beyond the realm of the real and the factual. Drawing a clear line of demarcation between "physics" and "mechanics," and suggesting to disregard the mechanical worldview altogether, Mach asserted that "the mechanical conception of nature . . . is not necessary for the knowledge of the phenomena and can be replaced just as well by another theory."[52] In the final part of his lecture, he aimed to strengthen his case by reformulating the principle of excluded perpetual motion independent from mechanics.[53]

The above example shows how Mach construed history as a tool to question, clarify, and redefine physical theories that he believed were unduly taken as authorities. In Mach's own words, he wrote history to "enlighten" the physics of his day.[54] It cannot be stressed enough that Mach was not interested in historiography as an end in itself. In his *Mechanics*, he made that explicit: "Without making the history of mechanics the chief topic of investigation, [we] consider its historical development so far as this is requisite to an understanding of the present state of mechanical science."[55]

## MACH'S HISTORICAL METHODS

Now that it has become clear that Mach construed history as a tool to "enlighten" physics, these questions arise: What did his historical toolkit consist of precisely? What practices characterized his historical research? From where did he draw his inspiration?

### Reading Historical Sources

Mach's historical writings were based on his reading of textual sources, both primary and secondary. On the basis of his notebooks and lecture notes, it is

52. Ibid., 54.
53. Ibid., 59–74.
54. On Mach's notion of "enlightenment," see Thomas Uebel, "Ernst Mach's Enlightenment Pragmatism: History and Economy in Scientific Cognition," in *Interpreting Mach*, ed. John Preston (Cambridge: Cambridge University Press, 2021), 84–102.
55. Mach, *Mechanics* (ref. 14), 8.

possible to reconstruct which sources Mach consulted, and when. Mach was familiar with a lot of secondary literature, including the work of the English historian of science William Whewell (1794–1866), the French physicist and historian Pierre Duhem (1861–1916), and the German historian of chemistry Hermann Kopp (1817–1892). He used their historical publications to prepare his lectures on subjects in physics, such as electricity.[56] Mach not only studied literature on the history of science but also broader cultural history. For example, he explored the cultural contexts of medieval knowledge making by reading medical historian Julius Hecker's *Die großen Volkskrankheiten des Mittelalters*, on epidemics, and the French historian Jules Michelet's *La Sorcière*, on witchcraft.[57] Especially witchcraft was a recurring theme in Mach's histories. He presented this as a highly relevant influence to the work of Johannes Kepler (1571–1630), Galileo, and others. During one public lecture, he even stated that natural science "began in the witch's kitchen."[58]

Mach regarded the study of primary sources as the foremost ingredient of historical inquiry: he was convinced that "proof must be drawn from original sources."[59] Thus, in his historical lecture on the principle of work conservation, he distinguished his own, source-based historical analysis of the principle of the impossibility to construct a *perpetuum mobile* from Joseph-Louis Lagrange's (1736–1813). Mach reproached Lagrange, the famous French mathematician, for his careless handling of primary sources in the historical introduction to his 1788 *Mécanique analytique*: "One soon finds, if one takes the trouble to consult the original [sources] themselves, that in his exposition this theorem does not play the part which it [actually] played."[60] Subsequently, he demonstrated his own familiarity with the original sources by providing lengthy quotations from different authors in different languages. For example, he cited Galileo's 1636 *Dialogue* in Italian, as well Simon Stevin's (1548–1620) *Hypomnemata mathematica* (1605) in Latin. By referring to specific passages from both works, he aimed to demonstrate that both Galileo and Stevin had used the principle of excluded perpetual motion in their work. In the case of Stevin, he highlighted the passage "*continuum et*

56. Ernst Mach, "Verzeichnis Vorlesungen Universität Wien," n.d., NL 174/0453, DM.
57. Ernst Mach, "Notizbuch," 17 May 1876, NL 174/513, DM.
58. Mach, "Why Has Man Two Eyes?" (ref. 25), 87.
59. Mach, *History and Root* (ref. 15), 20.
60. Ibid.

*aeternum motum efficient, quod est falsum*" ("a continuous and unending motion, which is false").[61]

Mach's notebooks also reveal glimpses of how he studied primary sources. In the notebook kept between January 1881 and February 1882, for example, we see Mach localizing a passage where Gottfried Wilhelm Leibniz (1646–1716) excluded the possibility of perpetual motion (figure 2). The notes reveal him pinpointing this exclusion between pages 148 and 156 in an article by Leibniz that criticized Cartesian dynamics and was published in the *Acta Eruditorum* in 1695. Right below, he has written a reminder for himself to check a passage in the work of Galileo on acceleration ("*Galilei nachsehn. Beschleunigte Bewegung*").[62] This remark illustrates that Mach, stimulated by his consultation of novel primary source material, kept returning to sources after he had first read them. This observation brings me to another aspect of Mach's historical practice: the comparison and ordering of historical sources and dates in lists and tables.

### Historical Lists

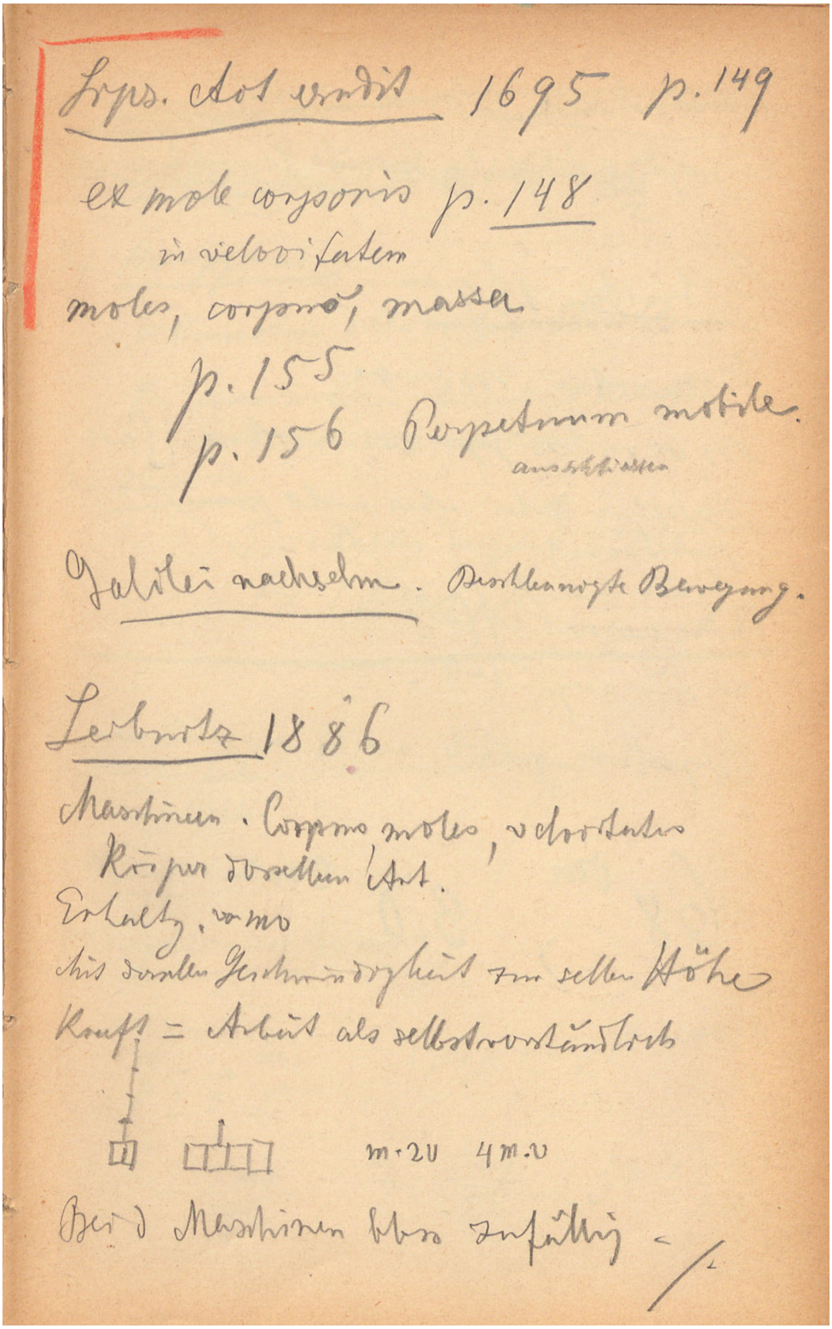
Mach's notebooks and lecture notes were both full of historical lists. These comprised enumerations of sources and their authors, linking them systematically. Sometimes the items on Mach's lists were organized according to specific themes, but more often they were compiled chronologically.[63] Mach used such lists to reconstruct and compare bibliographies of individual researchers. For example, on a notebook page from 1898 he listed five works by Galileo in chronological order (figure 3). These ranged from Galileo's 1610 *Sidereus Nuncius* to his 1638 *Two New Sciences* ("*Discorsi*").[64] On the next page, he made a similar list containing six publications by Kepler. The items of the list ranged from Kepler's 1604 *The Optical Part of Astronomy* ("*ad Vitellionem*") to his 1619

61. Ibid., 21. In the 1911 English translation, the original Latin and Italian have been largely translated into English. For Mach's original quotes, see Mach, *Geschichte und Wurzel* (ref. 15), 5–6, 8–9.

62. Ernst Mach, "Notizbuch," 26 Jan 1881, NL 174/521, DM.

63. On Mach's use of lists in his notebooks, see: Christoph Hoffmann, "1895: Ernst Mach sucht nach einem Thema," in *Improvisation und Invention Momente, Modelle, Medien*, ed. Sandro Zanetti (Zürich: Diaphanes, 2014), 369–83, on 375; Christoph Hoffmann, "Processes on Paper: Writing Procedures as Non-Material Research Devices," *Science in Context* 26, no. 2 (2013): 279–303.

64. Ernst Mach, "Notizbuch," Apr 1898, NL 174/545, DM.


Leips. Act. erudit. 1695 p. 149

ex mole corporis p. 148
in velocitatem
moles, corporis, massa
p. 155
p. 156 Perpetuum mobile
ausschliessen

Galilei nachsehn. Beschleunigte Bewegung.

Leibnitz 1886
Maschinen. Corporis moles, velocitates
Körper derselben Art.
Erhaltg. v. mv
Mit derselben Geschwindigkeit zur selben Höhe
Kraft = Arbeit als selbstverständlich

m·2v 4m·v

Bei d Maschinen bloss zufällig

**FIGURE 2.** Notes by Mach made while reading primary sources, in this case published articles by Leibniz. In the top six lines Mach traces how Leibniz excludes the possibility of perpetual motion (Perpetuum mobile ausschliessen). Right below is a reminder to consult some of Galileo's work (Galilei nachsehn). The fragment is from a notebook kept between January 1881 and February 1882. Source: NL 174/521, DM.

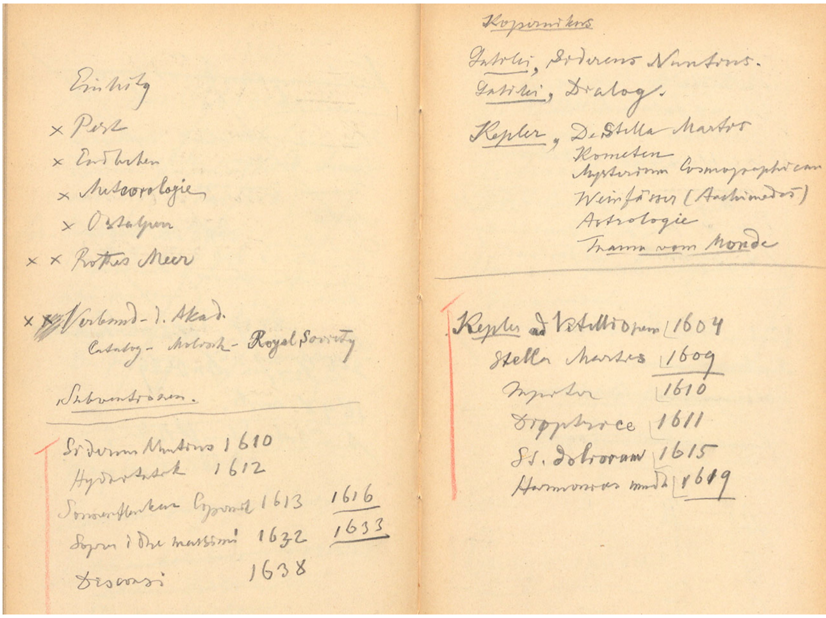


**FIGURE 3.** Lists of publications by Galileo and Kepler in Mach's notebook from 1898. Galileo's works are on the bottom of the left page, Kepler's are on the bottom of right page. On the top of the right page is a combined list of Galileo's and Kepler's publications. *Source*: NL 174/545, DM.

*Harmony of the Worlds* ("*Harmonices Mundi*"). A third list reveals how Mach connected the bibliographies of Galileo and Kepler.

Besides lists, Mach employed various other literary techniques to arrange and determine the interconnections of his historical source material. In an 1874 notebook, he listed twenty-two contributors to early modern scholarship on a timeline (figure 4).[65] These contributors were ordered chronologically. First in the timeline was Columbus, indicating the kind of broader cultural history that he understood his history of mechanics to be part of. Also included were names more familiar in the history of physics, such as Galileo, Kepler, and Newton. The timeline allowed Mach to gain an overview of when exactly his historical actors had lived and, on the basis of that, to determine who had been influenced by whom. To study such lines of influence he deemed crucial, for it enabled him to determine by whom and under what historical circumstances the path of factual description had been left.

65. Mach, "Notizbuch 509" (ref. 37).

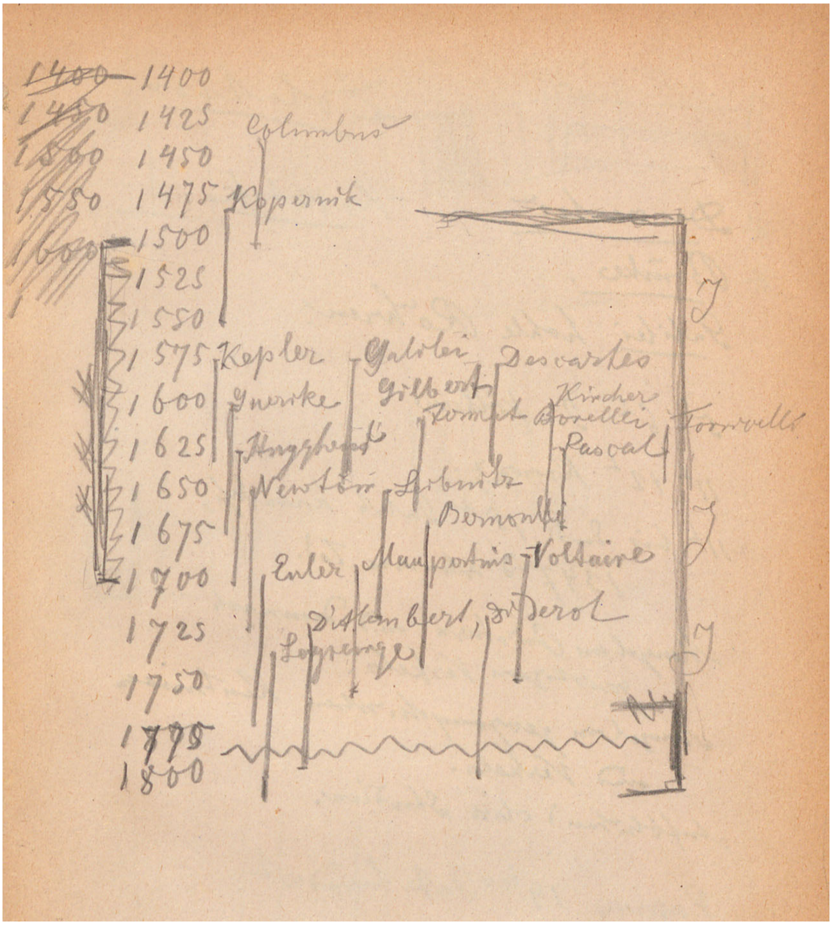



**FIGURE 4.** Mach ordering chronologically those he regarded as the main characters in the history of science between 1400 and 1800. The diagram is from a notebook dated 1874/75. Source: NL 174/509, DM.

Mach's use of lists and tables corresponded to common practices of German historians.[66] It also conformed to his own norm of economical description, which he propagated as the underlying epistemological foundation of all branches of *Wissenschaft*. Ordering and comparison guaranteed for Mach the unity of the empirical *Wissenschaften*—including disciplines as varied as

66. Benjamin Steiner, *Die Ordnung der Geschichte: historische Tabellenwerke in der frühen Neuzeit* (Köln: Böhlau Verlag, 2008).

geology, linguistics, and zoology, as well as physics and history. As he explained during an 1894 lecture in Vienna, comparative practices recurred across the disciplines:

> The zoologist sees in the bones of the wing-membranes of bats, fingers; he compares the bones of the cranium with the vertebras, the embryos of different organisms with one another, and the different stages of development of the same organism with one another. The geographer sees in Lake Garda a fjord, in the Sea of Aral a lake in process of drying up. The [linguist] compares different languages with one another, and the [areas] of [those] language[s].

He added that "like all other *Wissenschaften*, physics lives and grows by comparison."[67]

Given that Mach repeatedly emphasized that all empirically oriented knowledge disciplines relied on the same practices of economical description, including comparison and ordering, it is not surprising that such practices characterized his own historical studies. In a notebook kept between 1898 and 1900, Mach characterized the process of (historical) knowledge making as follows: "Many years of deep thinking. Combine and historically connect. Preserve. Compare. Organize."[68] It seems that Mach did not recognize the study of historical sources as a distinct form of empirical research, or at least he did not reflect on it as such. This resonates with Mach's view that no essential difference existed between the humanities and the natural sciences.

## Source Criticism

As Mach became more experienced as a historian, he increasingly acknowledged the relevance of another comparative method for historiography: source criticism. In the seventh German edition of *The Development of Mechanics* (1912), Mach identified a fundamental problem of historical research that could be solved only by means of this particular method.

> The knowledge of the development of a discipline relies on the study of writings in historical sequence and in their interconnection. For ancient

67. Ernst Mach, "On the Principle of Comparison in Physics," in *Popular Scientific Lectures*, trans. Thomas J. McCormack (Chicago: Open Court, 1895), 236–58, on 239. On Mach's comparative reasoning, see also Staley, "Sensory Studies" (ref. 21), 16ff.

68. Ernst Mach, "Notizbuch," 29 May 1898, NL 174/546, DM.

> times, of course, many sources are missing, and for other times the author is unknown or uncertain. In later centuries, especially before the invention of printing, the bad habit of an author seldomly referring to his predecessors when he uses their works was prolific. He would usually only do so when he thinks that he needs to contradict his predecessors. Under these circumstances, the designated study is made very difficult, which makes the highest demands on criticism.[69]

With "criticism" (*Kritik*), Mach referred to *Quellenkritik*, or source criticism.[70] Nineteenth-century German historians and philologists considered this to be the principal method of their disciplines.

The source-critical method had originated in early modern biblical and classical philology: the study of ancient and biblical texts.[71] By closely comparing various historical editions of a certain text, philologists aimed to identify translation and editing errors, with the ultimate aim of establishing a version of the text that approached its original as closely as possible. At the start of the nineteenth century, the originally philological method of source criticism was being appropriated by the first generations of German professional historians, who applied the method not to ancient and biblical sources but to texts of more recent origin.[72] The aim of the source criticism of historians was not to retrieve exact reconstructions of texts but rather to gain access to the historical events reported in these texts. In the nineteenth-century historical discipline, as in philology, source criticism comprised a range of comparative textual practices. These "consisted primarily in a close critical scrutiny of sources to determine their authorship, authenticity and reliability," as Frederick Beiser has put it.[73] By applying these practices,

69. Mach, *Mechanik* (7th ed.) (ref. 16), 75; also cited in Nemeth, "zur 'historisch-kritischen Methode'" (ref. 12), 29.

70. This was a different use of the term "criticism" than in the phrase *histo-risch-kritisch*, which recurred in Mach's book titles. Mach used the term *historisch-kritisch* to indicate his combination of historical and conceptual analysis. See Nemeth (ref. 12), 27–28.

71. Sebastiano Timpanaro, *The Genesis of Lachmann's Method*, trans. Glenn W. Most (Chicago: The University of Chicago Press, 2005).

72. James Turner, *Philology: The Forgotten Origins of the Modern Humanities* (Princeton, NJ: Princeton University Press, 2014), 197–209; Kasper Risbjerg Eskildsen, "Leopold Ranke's Archival Turn: Location and Evidence in Modern Historiography," *Modern Intellectual History* 5, no. 3 (2008): 425–53.

73. Frederick C. Beiser, *The German Historicist Tradition* (Oxford: Oxford University Press, 2011), 257.

historians aimed to distinguish between original reports of events and mere derivations, or, worse, fabrications.

It is relevant to note that in nineteenth-century German-speaking contexts, the philologically oriented disciplines outshined the natural-scientific ones in terms of intellectual and social prestige. This has already become apparent from the educational debates on the relatively subordinate role of the natural sciences in the *Gymnasium* curriculum, in which Mach took part. In general, the philologist's signature method of *Quellenkritik* was regarded as the benchmark for rigorous empirical *Wissenschaft*. Lorraine Daston and Glenn Most have rightfully pointed out that, in nineteenth-century Europe, "philology not only counted as *a* science, it was *the* science, the model of the highest form of knowledge." Within these contexts, Daston and Most further observe, natural scientists "often felt themselves to be at a disadvantage vis-à-vis their philologist colleagues."[74] In nineteenth-century German-speaking contexts, the originally philological method of source criticism provided a model of rigor and exactitude not only for textually oriented humanities scholars, including historians, but also for natural researchers, including physicists. In Mach's time, German physicists drew an analogy between textual criticism and their own empirical methods by fashioning exact measurement as a form of "severe criticism" (*scharfe Kritik*).[75]

Mach emphasized the importance of source criticism, in the citation above from 1912, after he had been confronted with its fruitful application by Emil Wohlwill. Directly following his appeal to the source-critical method, he discussed the contributions to the history of mechanics that Wohlwill had published in the years before. Further, in the preface to the 1912 edition of *The Development of Mechanics*, he wrote that "in an historical respect, the criticisms of Emil Wohlwill . . . were valuable and enlightening, especially on the period of Galileo's youthful work."[76] In the following section, I will further illustrate the role of source criticism in Mach's historiography on the basis of his interactions with Wohlwill, who assisted Mach in revising his history of mechanics according to the latest source-critical norms and results.



74. Lorraine Daston and Glenn W. Most, "History of Science and History of Philologies," *Isis* 106, no. 2 (2015): 378–90, on 384.

75. Rudolf Stichweh, "Kulturelle Motive für Präzisionsmessungen," in *Genauigkeit und Präzision in der Geschichte der Wissenschaften und des Alltags*, ed. Dieter Hoffmann and Harald Witthöft (Braunschweig: Physikalisch-Technische Bundesanstalt, 1996), 33–52, on 44.

76. Mach, *Mechanics* (ref. 14), xxvii.

## MACH AND WOHLWILL'S SOURCE CRITICISM

Emil Wohlwill built a career as an industrial chemist and as a teacher of physics and chemistry in the city of Hamburg.[77] Parallel to this career, he also became successful as a historian of the natural sciences. His first historical studies explored developments in chemistry, in particular in the history of isomorphism.[78] After 1867, the history of physics became Wohlwill's main focus. He was especially interested in Galileo's contributions: writing a biography of Galileo became Wohlwill's lifetime project on which he spent nearly all his free hours.

Wohlwill conformed to contemporary standards of professional historical research, even though he had enjoyed no disciplinary training in history. His historical publications contained many references to archival sources, and heavily relied on Italian historian Antonio Favaro's (1847–1922) *Edizione Nazionale*. Published between 1890 and 1909, the twenty volumes of the *Edizione Nazionale* comprised a complete and accurate edition of Galileo's works, including many previously unpublished letters, documents, and manuscripts from Italian archives.[79] Wohlwill was in contact with Favaro, and received a free copy of his source edition from the Italian ministry of education.[80] The archival sources made available in the *Edizione Nazionale*, Wohlwill said, allowed him to substantiate his historical account of Galileo's life and work by using "an extremely meticulous reproduction of the source material."[81] Additionally, in 1891, he traveled to the Vatican archives to study sources related to Galileo's trial.[82]

In addition to his emphasis on the historical knowledge contained in previously unexplored archival sources, by which he conformed to the nineteenth-century "archival turn" of the German historical discipline, Wohlwill wholeheartedly committed to the historian's research method of source criticism.[83] For

77. Hans-Werner Schütt, *Emil Wohlwill, Galilei-Forscher, Chemiker, Hamburger Bürger im 19. Jahrhundert* (Hildesheim: HA Gerstenberg, 1972), 18–19.

78. Stefano Salvia, "Emil Wohlwill's 'Entdeckung des Isomorphismus': A Nineteenth-Century 'Material Biography' of Crystallography," *Ambix* 60, no. 3 (2013): 255–84.

79. Giuseppe Castagnetti and Michele Camerota, "Antonio Favaro and the Edizione Nazionale of Galileo's Works," *Science in Context* 13, no. 3/4 (2000): 627–31.

80. Emil Wohlwill, *Galileo und sein Kampf für die Copernicanische Lehre*, vol. 1 (Hamburg: Leopold Voss, 1909), ix.

81. Ibid., vi.

82. Schütt, *Wohlwill, Galilei-Forscher* (ref. 77), 20–21.

83. Eskildsen, "Ranke's Archival Turn" (ref. 72).

instance, he extensively compared primary sources, including various editions and translations in multiple languages of one and the same source, to establish their individual authenticity and mutual relationships. Further, he consistently inspected the reliability of primary sources by questioning the trustworthiness of their authors.

That such procedures characterized Wohlwill's historiography becomes evident from his 1865 article on the history of the thermometer.[84] By comparing a multitude of sources, including translations in different languages, Wohlwill rebutted the claim that Dutch engineer Cornelis Drebbel (1572–1633) had invented the thermoscope (a late-sixteenth-century precursor of the thermometer). He located the origin of this historical myth in a 1636 Latin translation of a 1624 French book by the Jesuit scholar Jean Leurechon (1591–1670). Wohlwill established that this translation by the Dutch physician Caspar Ens was a literal translation of the original, except for one crucial difference:

> Perhaps the only word that the editor has allowed himself to include is *Drebilianum*. The Frenchman writes: "*du thermomètre ou instrument pour mesurer les degrez de chaleur ou de froidure qui sont en l'air*." Ens translates: "*De thermometra sive instrumento Drebiliano quo gradus caloris frigoris que aëra occupantis explorantur*." The word "*Drebiliano*" has no counterpart in the editions of the French texts that I am familiar with; it is also absent in Schwenter's German edition (*Mathematische Erquickstunden*, 1686), in the English, and—what is particularly important—in the Dutch translation (*Mathematische Vermaecklyckheden*, third edition, 1644).[85]

So, by applying the source-critical method, that is, by comparing multiple sources and editions in different languages, Wohlwill established the origin of the historical claim that Drebbel constructed the first thermometer: "Most probably, all later mentions of this very man as the inventor of the thermoscope can be traced back to this unjustified translation."[86] Wohlwill concluded by arguing that the thermometer had been invented in Italy by Galileo and the physician Santorio Sanctorius (1561–1636), and that Drebbel had probably only been introduced to the instrument during a visit to England.[87]

84. Emil Wohlwill, "Zur Geschichte der Erfindung und Verbreitung des Thermometers," *Annalen der Physik* 200, no. 1 (1865): 163–78.

85. Ibid., 167.

86. Ibid.

87. Ibid., 173.

Thus, Wohlwill illustrated in his writings that any historical account should be grounded in the critical examination of primary sources and their authors, that is, in source criticism. To this end, he proceeded in a philologically exact manner, studying texts closely and comparatively, thereby conforming to the disciplinary norms of German historians. Moreover, Wohlwill stressed that the results of historiography were always provisional, since they depended on the available collection of source material, which could always be enriched, as had happened in the case of the *Edizione Nazionale*.[88]

Wohlwill championed these historiographical norms and practices while evaluating the work of Mach. In an 1884 publication on the history of the law of inertia, for example, he discussed the recently published first edition of Mach's *Mechanics*.[89] He acknowledged that Mach had reached reasonable conclusions about the development of Galileo's thought considering the sources he had consulted. However, he remarked that his Austrian colleague had failed to include essential sources in his analysis. Mach had focused particularly on Galileo's 1638 *Discorsi*, neglecting Galileo's older works, particularly his *Dialogue* from 1632. According to Wohlwill, Galileo's earlier work shed a different light on the development of Galileo's understanding of the law of inertia.

Wohlwill further claimed that Mach had misconstrued the relationship between Galileo and the Bohemian physician Marcus Marci (1595–1667). In the first edition of his *Mechanics*, Mach had highlighted Marci's work on the collisions of bodies, and suggested that Marci had reached his results independently from Galileo: "Although Galileo's *Discorsi* had been published a year before, one cannot assume that Marci knew this work, given the circumstances in Central Europe caused by the Thirty Years' War," Mach argued. The supposed originality of Marci's 1639 book *De proportione motus* had led Mach to portray Marci as "a man of significant accomplishments. His writings are a dignified and still hardly noticed object for historical researchers in the area of physics."[90] Wohlwill contested Mach's claims on the basis of a textual comparison of Galilei's 1632 *Dialogue* and Marci's 1639 *De proportione motus*: "From a detailed comparison with the text '*de proportione motus*,' I have become convinced that Marci was well acquainted with Galileo's *Dialogue*, which was

88. See, e.g., Emil Wohlwill, "Hat Leonardo da Vinci das Beharrungsgesetz gekannt?" *Bibliotheca Mathematica* 2 (1888): 19–26, on 24.

89. Emil Wohlwill, *Die Entdeckung des Beharrungsgesetz* (Weimar: Hof-Buchdruckerei, 1884), 162–63.

90. Mach, *Mechanik* (1st ed.) (ref. 14), 284.

published in 1632 and translated into Latin in 1634."[91] According to Wohlwill, Marci's *De proportione motus* was actually little more than a direct derivative of Galilei's *Dialogue*.

Mach welcomed Wohlwill's source-critical remarks. In the third edition of *The Development of Mechanics*, dated 1897, he followed Wohlwill in claiming that Marci was familiar with Galileo's earlier works.[92] Moreover, he put much more emphasis than he had before on historical continuities between ancient and modern times. Thus, he conceded that "Galileo's predecessors and contemporaries, even Galileo himself, had arrived at the law of inertia only very gradually, while freeing themselves from Aristotelian notions."[93] For example, Mach admitted that Galileo still attributed an exceptional role to uniform circular motion and uniform horizontal motion, precisely as Aristotelian philosophy had dictated. Following these remarks, Mach expressed his gratitude toward Wohlwill's historical research, since it had demonstrated "that Galileo experienced difficulties in achieving full clarity with regard to his own groundbreaking ideas and frequently relapsed into older views."[94]

In addition to referencing each other's work in their publications, Mach and Wohlwill maintained a longstanding correspondence. Their correspondence reveals how Mach accepted many of Wohlwill's specific historical claims, as well as his source-critical methodology. In 1911, now well aware of Wohlwill's critical handling and extensive knowledge of primary sources, Mach turned to Wohlwill to request his help in revising his *Mechanics* according to the latest historiographical insights and standards. Wohlwill responded to Mach's request eagerly, and sent his colleague a sixteen-page evaluation of his manuscript. Certainly, this was a lot more than the "brief rectification" that Mach had originally asked for.[95]

The sixteen-page report that Wohlwill sent to Mach was divided into six sections; each dealt with different topics and contained numerous suggestions for improvement. Among many suggestions, some of which were related to Stevin but most to Galileo, Wohlwill again criticized Mach's persistently glorifying portrayal of Marcus Marci. He reminded his colleague that he had long identified Galileo's 1632 *Dialogue* as the actual source of Marci's theory of

91. Wohlwill, *Die Entdeckung des Beharrungsgesetz* (ref. 89), 163.

92. Ernst Mach, *Die Mechanik in ihrer Entwickelung: Historisch-kritisch dargestellt*, 3rd edition (Leipzig: F. A. Brockhaus, 1897), 339.

93. Mach, *Mechanik* (3rd ed.) (ref. 92), 132–33.

94. Ibid.

95. Emil Wohlwill to Ernst Mach, 4 Sep 1911, NL 174/3248, DM, 16 pp.

dynamics, and suggested: "Perhaps you could add the following words to p. 349, line 13 from the bottom: 'that he was aware of Galileo's Dialogue Concerning the Two Chief World Systems.'"[96] Moreover, Wohlwill again urged Mach to be more exact regarding the chronology of Galileo's work. For example, he challenged Mach's historical depiction of Galileo's discovery of the law of free fall, pointing out the availability of new sources, including the many manuscripts and letters in the *Edizione Nazionale*.

Mach incorporated many of Wohlwill's suggestions in the 1912 edition of his *Mechanics*. He conceded, eventually, referring to Wohlwill's publications, that "Marci emphatically cannot be considered as having advanced dynamics in the direction taken by Galileo."[97] Further, Mach explained that while he had originally mainly consulted Galileo's 1638 *Discorsi*, he now also relied on some of Galileo's earlier writings, which had recently come to his attention. Referring to the first part of Wohlwill's biography of Galileo, he admitted that these newly available writings by Galileo had led "to different views on the course of his development. With respect to these I adopt, in essentials, the conclusions of E. Wohlwill."[98] As it turns out, Mach had implemented the following suggestion from Wohlwill's report almost literally:

> The discussion on p. 129 could perhaps begin with a remark that the analysis of the historical course of his discovery in the previous editions of the *Mechanics* was based on the concluding words from [the] 1638 [*Discorsi*], but that the original writings of Galileo, which have now become known, lead to a view that deviates in several respects.[99]

Mach likely also followed up Wohlwill's recommendation to pay a visit to the *Wiener Hofbibliothek*. There, Wohlwill had stressed in the letter accompanying his report, Mach would be able to consult Galileo's original documents himself in the eighth volume of the *Edizione Nazionale,* to verify Wohlwill's corrections.[100] Following Wohlwill's instructions, Mach included several references to this edition in the 1912 version of the *Mechanics*.[101]

By cooperating with Wohlwill, Mach was inspired to substantiate his historical narrative with a critical investigation of the available source material. In

96. Ibid., 15–16.
97. Mach, *Mechanics* (ref. 14), 397–398.
98. Ibid., 155.
99. Wohlwill to Mach, 4 Sep 1911 (ref. 95), 11.
100. Ibid., 12.
101. Mach, *Mechanik* (7th ed.) (ref. 16), 121, 122.

doing so, he complied with the methodological norms cultivated by nineteenth-century historians. Although he did not apply the source-critical method as thoroughly as Wohlwill, Mach appropriated source criticism to the point where he explicitly advocated its fundamental relevance to historical study, and thus, given his conviction that historical study formed an integral part of physics, also to physics.

## NINETEENTH-CENTURY PHYSICISTS AS HISTORIANS

The case of Mach shows that the method of source criticism was not relevant only for historians and philologists. After Wohlwill had intervened, he fashioned the method as a crucial aspect of knowledge production in physics. It turns out that Mach was only one among several prominent nineteenth-century natural scientists for whom source criticism was a relevant research method. Helmholtz, for example, appropriated the method into his research as well.

The work of Helmholtz cut across the disciplines of physics, physiology, and psychology. In this respect, it was similar to Mach's, whose psychophysical experimental investigations were in fact directly inspired by Helmholtz.[102] Like Mach, Helmholtz believed that perception depended on historical circumstances. In contrast to Mach, however, Helmholtz also committed to ahistorical, *a priori* laws, which explains why they had different opinions about the mechanical worldview.[103] Notwithstanding these differences, Mach and Helmholtz practiced similar historical methods, including source criticism. Helmholtz relied on the source-critical method when he compared Ancient Greek and Persian musical scales to determine their historical relationship, in the early 1860s.[104] He performed this historical-comparative investigation in the context of his experimental studies of auditory physiology. As Julia Kursell has argued, Helmholtz read "sources for ancient music theory that [philologists] had made accessible during the first half of the nineteenth century [as]

102. On the relation between Mach and Helmholtz's psychophysical investigations of hearing: Hui, *The Psychophysical Ear* (ref. 20), 94–102.

103. Patton, "Abstraction, Pragmatism, and History" (ref. 14), 145–47.

104. Julia Kursell, "Fine-Tuning Philology: Helmholtz's Investigation into Ancient Greek and Persian Scales," *History of Humanities* 2, no. 2 (2017): 345–59. See Hermann von Helmholtz, "Über die arabisch-persische Tonleiter," *Verhandlungen des naturhistorisch-medizinischen Vereins zu Heidelberg*, no. 2 (1862): 216–17.

testimonies for modes of listening that had emerged under different material conditions than those of his own times, and he then took his readings back to his 'laboratory.'"[105] Thus, Helmholtz interlinked natural science and the historical-comparative study of music. The source-critical method was part of his toolkit to study the complex interplay of the human and natural world.

Nineteenth-century German-speaking botanists, as well, applied source criticism to study the natural world. As Marianne Klemun has shown, the method was employed by botanist Anton Kerner von Marilaun (1831–1898), a contemporary of Mach also from Vienna.[106] Kerner was equally historically sensitive as Mach, claiming that "each of our theories has its history," while mocking those natural scientists representing the "laws of the presents as infallible and immutable."[107] Analogous to how Mach combined history and physics, Kerner merged historical and botanical research. As Deborah Coen has argued, Kerner unified historical and botanical research by interpreting the floral world as an "archive"; his "ambition was to tell a history of all of Austria-Hungary, and to do so with flowers."[108] For example, Kerner compared numerous textual sources to reconstruct historical genealogies of plant names. His main finding was that many of the plants growing in the gardens of German farms had also existed in Antiquity, although the Ancients had known them by different names. Thus, Kerner managed to show that there was historical continuity between Ancient and modern times, by applying methods drawn from the humanities to what he considered to be essentially botanical questions.[109]

The cases of Mach, Helmholtz, and Kerner demonstrate that, even while the *Geisteswissenschaften* and *Naturwissenschaften* were being defined as distinct branches of knowledge, humanities scholars and natural scientists shared methods. Among the natural scientists employing historical methods were still

105. Kursell, "Fine-Tuning Philology" (ref. 104), 346.

106. Marianne Klemun, "Historismus/Historismen – Geschichtliches und Naturkundliches: Identität – Episteme – Praktiken," in *Wissenschaftliche Forschung in Österreich 1800–1900: Spezialisierung, Organisation, Praxis*, ed. Christine Ottner, Gerhard Holzer, and Petra Svatek (Göttingen: V&R unipress, 2015), 17–42, on 33–34. On Kerner's historical-botanical research, see also Deborah R. Coen, *Climate in Motion: Science, Empire, and the Problem of Scale* (Chicago: The University of Chicago Press, 2018), 25–28, 274–311.

107. As cited in Coen, *Climate in Motion* (ref. 106), 310–11.

108. Ibid., 292.

109. Anton Kerner, "Flora der Bauerngärten in Deutschland," *Verhandlungen des Zoologisch-Botanischen Vereins in Wien* 5 (1855): 787–826.

other physicists than Mach and Helmholtz.[110] However, not all physicists using historical methods understood these methods to form an integral part of their discipline. This is clearly evident from the views of physicists studying the history of physics simultaneously with Mach. Although many German-speaking physicists engaged in historical studies over the course of the nineteenth century, most thought of the history of physics and physics as separate enterprises.

To further clarify this difference in opinion among nineteenth-century physicists writing history, the remaining part of this section will compare Mach's historical aims and methods to those of another prominent German-speaking physicist from the nineteenth century: Johann Christian Poggendorff, the Berlin-based professor and editor of the journal *Annalen der Physik und Chemie*. While Poggendorff practiced similar historical methods as Mach, including source criticism, he did not regard them as tools for physics. Instead, Poggendorff considered the history of physics as a scholarly enterprise in and of itself.

#### Poggendorff Compared to Mach

Poggendorff's conception of proper scientific method was similar to Mach's. As one of his obituarists put it, he "attached most value to the experimental basis [of physics], and strongly refrained from idle speculation."[111] Poggendorff's contributions to physics, most of which were experimental and dealt with electricity and magnetism, met these demands. His empiricist attitude was also reflected in the editing of his journal, for example in his famous rejection of Helmholtz's 1847 essay on the conservation of work—the one that would later be subjected to a historically based criticism by Mach. Poggendorff regarded Helmholtz's work as too speculative and insufficiently factual in nature to be published in his journal.[112] Besides his editorial and experimental activities, Poggendorff lectured on the history of physics at the University of Berlin, from the mid-1830s until the 1870s. Among his many auditors

110. On history written by nineteenth-century physicists, see Wolfgang Schreier, "Deutschsprachige physikhistorische Literatur aus dem 19. Jahrhundert: Struktur, Diktion, Wandlung," *NTM Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin* 7 (1999): 129–39.

111. Wilhelm Barentin, "Johann Christian Poggendorff," *Annalen der Physik und Chemie* 236, no. 1 (1877): v–xxiv, on xi.

112. David Cahan, *Helmholtz: A Life in Science* (Chicago: The University of Chicago Press, 2018), 61ff.

during these decades were the young Emil Wohlwill, who attended in the 1850s, and Rudolf Clausius, who attended in 1843.[113] In 1879, Poggendorff's lectures were published posthumously.[114]

While lecturing on the history of physics and editing the *Annalen*, Poggendorff found the time to produce two other major historical works. In 1853, some two decades after he had started giving historical lectures, Poggendorff published the first: the "*Lebenslinien zur Geschichte der exacten Wissenschaften*."[115] He explained in the introduction to this little book that his lectures on the history of physics had inspired him to start collecting biographical data of natural scientists.[116] He presented the data he had managed to collect thus far in a list of fourteen pages, which gave an alphabetical overview of hundreds of researchers, mentioning their lifetime and most important scientific contributions.[117] Attached to his alphabetical list were three timelines (called "*Lebenslinien*," see figure 5). Poggendorff explained that he had chosen to present these data visually, in "*anschauliche Form*."[118] For this, he relied on the graphic historical method of the timeline, which had been introduced by the British polymath Joseph Priestley in his 1765 *Chart of Biography*.[119]

After publishing the *Lebenslinien,* Poggendorff continued to collect and order historical data. This resulted in his second major contribution to the history of the natural sciences: in 1863, he published the "*Biographisch-Literarisches Handwörterbuch zur Geschichte der exacten Wissenschaften*."[120] This two-volume, 1500-page "biographical-literary dictionary" was the product of an arduous historiographical undertaking that had taken him fifteen years to complete. It became a highly valuable literary tool for many historians and

113. Clausius's notes of Poggendorff's lectures have been preserved: Rudolf Clausius, "Geschichte der Physik bei Poggendorff" (1843), HS6399, DM.

114. Johann Christian Poggendorff, *Geschichte der Physik: Vorlesungen gehalten an der Universität zu Berlin* (Leipzig: J. A. Barth, 1879).

115. Johann C. Poggendorff, *Lebenslinien zur Geschichte der exacten Wissenschaften* (Berlin: Duncker, 1853).

116. Poggendorff, *Lebenslinien* (ref. 115), v.

117. Ibid., 1–14.

118. Ibid., v.

119. Daniel Rosenberg, "Joseph Priestley and the Graphic Invention of Modern Time," *Studies in Eighteenth-Century Culture* 36, no. 1 (2007): 55–103.

120. Johann C. Poggendorff, *Biographisch-literarisches Handwörterbuch zur Geschichte der exacten Wissenschaften*, vol. 1 of 2 (Leipzig: Johann Ambrosius Barth, 1863).

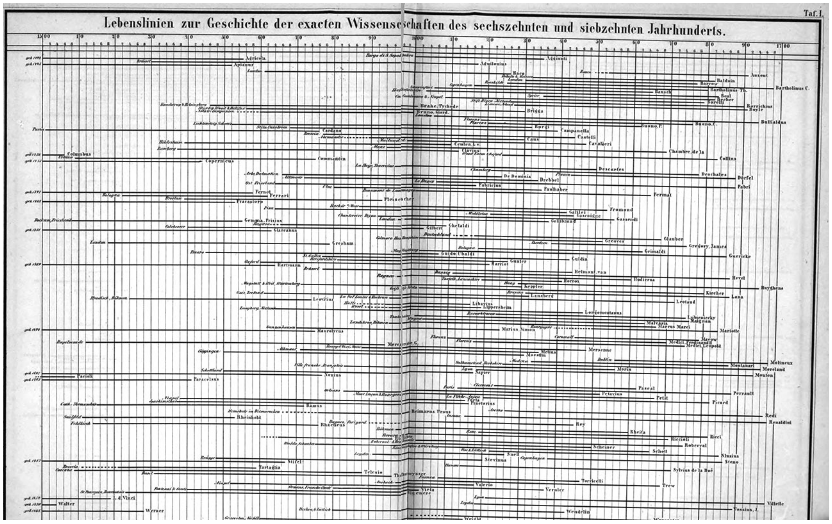



**FIGURE 5.** One of Poggendorff's timelines, visualizing the lifetimes of researchers in the sixteenth and seventeenth century. Source: Poggendorff, *Lebenslinien* (ref. 115).

natural scientists, including Mach.[121] Poggendorff's dictionary contained biographical and bibliographical entries of "mathematicians, physicists, chemists, mineralogists, geologists, etc. of all peoples and times," as read its ambitious subtitle. He had managed to fill one-seventh of these entries (1169 of the 8447 in total) with reliable biographical and bibliographical data (figure 6). To this end, he had consulted numerous catalogues, encyclopedias, and other literary tools in Berlin's Royal Library. Moreover, he had been assisted by an international network of about a dozen other historically minded natural scientists, who had roamed Europe's libraries looking for bibliographical data and biographical information unknown to Poggendorff, and reported back to him.[122] Through this ambitious bio-bibliographical project, Poggendorff gained a reputation for his "love for orderliness" (*Ordnungsliebe*).[123] Illustratively, Alexander von Humboldt wrote to him, admiringly, after receiving a draft of the first volume of his dictionary in 1858: "Such an undertaking could only be

121. Mach mentions Poggendorff's dictionary in one of his notebooks; Ernst Mach, "Notizbuch," 12 Apr 1873, NL 174/507, DM.

122. Correspondence between Poggendorff and members of this network (which included physicists Joseph Plateau, Anders Ångström, and Friedrich Kohlrausch, among others) has survived: Johann C. Poggendorff to Académie Royale, 22 Feb 1858, HS3464, DM; Johann C. Poggendorff to Rudolf Wolf, 8 Nov 1860, HS-651894, Bayerische Staatsbibliothek.

123. Barentin, "Johann Christian Poggendorff" (ref. 111), x.

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einige derselben besitzen auch ein physikal. Interesse, so seine Theorie des Sehens, die noch **Brewster** kürzlich (The Stereoscope etc., Lond. 1856, p. 6) hervorhebt, und dabei als Quelle citirt: De usu partium corporis humani, Lugduni 1550, p. 593.

**Galeotti,** Henri Guillaume. — Director des Gartens der Société royale d'horticulture zu Brüssel, in St. Josse-ten-Noode wohnhaft *(BAB)*,
geb. 1814, Sept. 8, Paris,
gest. 1858, März 14, Brüssel *(Zt)*.
Mém. sur la constitution géognost. de la province de Brabant (Mem. cour. acad. Brux. XII, 1835). Voyage au Coffre de Perote, au Mexique (Ib. III, 1836). Sur un gite de mercure dans le sol tertiaire récent du Gigante, au Mexique (Ib. V, 1838). Notice géolog. sur les environs de S. José del Oro (Ib. id.). Notice géognost. sur les mines d'alun de la Barranca de Toliman (Ib. id.). Coup d'oeil sur la Laguna de Chapala, au Mexique (Ib. VI, 1839). Aperçu géonost. sur les environs de la Havane (Ib. VII, 1841). Sur les tremblements de terre et les étoiles filantes, au Mexique (Ib. VIII, 1841). — Botanisches.

**Galiano,** Dionisio Alcalá. — Capitän in d. span. Kriegsmarine *(Navarrete, Opusc. T. I)*,
geb. 1760, Oct. . . , Cabra, Prov. Cordova,
gest. 1805, Oct. 21, in d. Schlacht von Trafalgar.
Begleitete **Malaspina** auf seiner Reise um die Welt und machte dabei viele geogr. Ortsbestimmungen in Amerika. Siehe **v. Zach's** Monatl. Corr. XIV u. Corr. astron. XV.

**Galien,** Joseph. — Dominicaner, Prof. d. Philosophie und Theologie an d. Univ. zu Avignon *(BG)*,
geb. 1699, . . . St.-Paulien bei Puy,
gest. 1782, . . . Avignon.*
L'Art de naviguer dans les airs, précédé d'un Mém. sur l'origine et la formation de la grêle, 16°, Avignon 1755, 2^me^ édit. 1757 (Darin schon die Grundsätze der Luftschiffahrt ausgesprochen, insofern **G.** vorschlägt, grosse Ballone mit einer leichten Gasart [mit atmosph Luft aus höheren Regionen!] zu füllen).

* gest. 1762, . . . Puy *(B)*; ist falsch *(BG)*.

**Galigai,** s. Ghaligaj.

**Galilei,** Vincenzio.* — Unbemittelter Edelmann, der, wenigstens nebenher, einen Woll- oder Tuchhandel getrieben zu haben scheint. Vater des grossen Physikers *(Nelli)*,
geb. 1520, . . . . Florenz,**
gest. 1591, Juli 2, Florenz.
Dialogo della musica antica e moderna in sua difesa contra **G. Zarlino**, fol., Firenze 1581. Fronimo, dialogo sopra l'arte del bene intavolare ed rettamente sonare la musica, fol. Venezia 1584. Discorso intorno all' opere di **G. Zarlino** ed altri importanti particolari attimenti alla musica, Firenze 1589.

* Wird von Einigen Vincenzio di Michelangelo Galilei genannt, vermuthlich weil sein Vater mit Vornamen Michel Angelo hiess. Die Familie führte in früheren Zeiten den Namen Bonajuto. Der Erste, der sich Galileo nannte, war ein Arzt, der 1435 Medicin an der Univ. zu Florenz las und daselbst 1445 auch das Amt eines Gonfaloniere di Giustizia bekleidete. Die lateinische Inschrift seines Monuments in der Kirche Santa Croce zu Florenz nennt ihn: Galilaeus de Galileis olim Bonajutis.
** geb. 1533 etwa, . . . *(BG)*.

**Galilei,** Galileo. — Bezog schon im 17. Jahre die Univ. zu Pisa, war dann Prof. d. Mathematik daselbst von 1589 bis 1592, darauf Prof. derselben an d. Univ. zu Padua (1593—1609) und nun wieder Prof. zu Pisa, sowie (seit 1610) erster Mathematiker und Philosoph des Grossherzogs Cosimo II. von Toscana und später auch dessen Nachfolgers Ferdinand II. Nach seinem weltberühmten Kampf mit der römischen Hierarchie, der bekanntlich damit endete, dass er durch die Inquisition (wahrscheinlich nach vorheriger Anwendung der Tortur) gezwungen ward, am 20. Juni 1633 die Lehre von der Bewegung der Erde als ketzerisch zu verfluchen und ihr abzuschwören, wohnte er erst in Siena, später auf dem Lande bei Florenz, zuletzt in der Villa Giojello bei Arcetri. Seit 1637 auf auf beiden Augen erblindet *(Nelli) (Frisi, Elogi di Galileo etc., 8°, Milano 1778) (Jagemann, Gesch. d. Lebens u. d. Schrift. v. G. G.,* Weimar 1783*) (Brewster, Life of G. etc.,* Lond. 1841*) (Marini, Galileo e l'Inquisizione,* Roma 1850*) (Libri, hist. math.* IV, *deutsch v. Carové) (VJ) (T.* VIII*) (B) (BN) (BG)*,
geb. 1564, Febr. 18, Pisa,*
gest. 1642, Jan. 8, b. Arcetri, Tosc.
Von ihm selbst oder bei seinen Lebzeiten wurden folgende Schriften veröffentlicht, die meistens mehrfach edirt und übersetzt worden sind: Le operazioni del compasso geometrico e militare (der Proportionalzirkel, erfunden 1597), fol. Padova 1606. Difesa etc. contro alle calunnie ed imposture di **Baldassare Capra** etc., 4°, Venezia 1607. Sidoreus Nuncius, magna longeque admirabilia spectacula pandens, suspiciendaque proponens unicuique, praesertim vero Philosophis atque Astronomis, quae a **Gal. Gal.** etc., perspicilli nuper a se reperto beneficio, sunt observata in Lunae facie, Fixis innumeris, Lacteo circulo, Stellis nebulosis, apprime vero in quatuor planetis circa Jovis stellam disparsibus intervallis atque periodicis celeritate mirabili circumvolutis; quos nemini

**FIGURE 6.** Fragment from Poggendorff's dictionary, listing biographical and bibliographical data of Galileo. Source: Poggendorff, Biographisch-literarisches Handwörterbuch, vol. 1 (ref. 120), 831–932.

accomplished by you! No one else but you could master such an amount of material!"[124]

There were close similarities between the methods that Mach and Poggendorff used to delve into the history of their discipline. Both made frequent use of lists and tables to organize and grasp the interconnections between historical sources and events. Moreover, Poggendorff, like Mach, regarded source criticism as a crucial historical practice. Indeed, what German historians understood as source criticism—dating and establishing the authenticity and reliability of textual sources—was central to Poggendorff's biographical-literary project. In the preface to his published lectures, Poggendorff further underlined the importance of "severe criticism" (*strenge Kritik*) in order to fulfill the "very difficult task of the historian."[125] His commitment to source criticism becomes further apparent from his published lectures, for example in his critical treatment of sources that made historically unsubstantiated claims about the invention of the telescope and the thermometer.[126]

Although Mach and Poggendorff used similar methods to write history, their aims were different. Poggendorff was keenly interested not just in the historical development of ideas and instrumentation but also in the kind of biographical details that Mach consciously excluded from his historical studies. This was mainly because Poggendorff considered the history of physics to be a project on its own. In the preface to his published lectures, Poggendorff demarcated physics from its history by stating, "Those who want to teach or learn *Wissenschaft* only have to understand its present state. They reach for the ripe fruits, and care little about how and where they have grown."[127] Clearly, these remarks were diametrically opposed to Mach's attempts to integrate physics and historiography, as to enlighten current physics.

The comparison between Mach and Poggendorff makes clear that while Mach was not the only physicist who shared research methods with historians, his aim to integrate these methods into the toolkit of the physicist was not common. In fact, most nineteenth-century physicists writing history, Poggendorff included, considered the history of natural science as an autonomous enterprise.

124. Quoted in Hans Wussing, "Der 'Poggendorff'—Bestand und Wandel," in *J.C. Poggendorff—Leben und Werk*, ed. Heiner Kaden and Benno Parthier, 2005, 7–10, on 8.

125. Poggendorff, *Geschichte der Physik* (ref. 114), 1–3.

126. Ibid., 175–89, 255ff.

127. Ibid., 1.

Still other natural scientists from the period engaged with historical studies to demarcate the natural sciences from other branches of knowledge making, including historiography. As Rachel Laudan has pointed out, "an important strategy" for historically active natural scientists "was sharply to contrast knowledge of the natural world with other forms of knowledge."[128] To be sure, Mach's historiography can also be seen as a form of boundary work, since it demarcated physical theories relying on economical description from those which did not. However, if Mach practiced historical methods, he believed that he was contributing directly to physics.

### Between Disciplines

By discussing the historical aims and methods of Poggendorff and comparing them to Mach's, I have aimed to make clear that although some of Mach's peers practiced the very same historical methods, they generally did so with different aims. Unlike Mach, they distinguished between the practice of physics and the writing of its history. Such a distinction was also maintained by French physicist and historian Pierre Duhem, who rejected Mach's "subjective" application of history as a mere means.[129] In a critical 1903 review of the first French translation of *The Development of Mechanics*, Duhem noted with disapproval that "Mr. Mach wants to be a physicist and logician rather than a historian."[130] Even Wohlwill was interested in the history of physics for utterly different reasons from Mach's. The main motivation underlying Wohlwill's historical studies was to "understand people and processes."[131] Mach, on the other hand, performed historical studies to better understand the natural world. Put differently, Wohlwill and Mach studied the same sources by the same methods, but for different reasons: while Wohlwill studied Galileo's writings to better understand Galileo, Mach did so to reflect on and improve contemporary theories of physics.

With the above differences in mind, it may come as little surprise that, when trying to make historical practice an integrated part of physics, Mach

128. Rachel Laudan, "Histories of the Sciences and Their Uses: A Review to 1913," *History of Science* 31, no. 1 (1993): 1–34, on 1.

129. Klaus Hentschel, "Die Korrespondenz Duhem-Mach: Zur 'Modellbeladenheit' von Wissenschaftsgeschichte," *Annals of science* 45, no. 1 (1988): 73–91, on 88.

130. Pierre Duhem, review of *La Mécanique. Étude historique et critique de son Développement*, by Ernst Mach, *Bulletin des Sciences et Mathématiques* 27, no. 2 (1903): 261–83.

131. Emil Wohlwill, "The Discovery of the Parabolic Shape of the Projectile Trajectory," *Science in Context* 13, no. 3–4 (2000): 645–80, on 663.

experienced indifference among his colleagues in physics. Writing in 1872, he remembered that after he had first approached mechanics historically, during the 1860s, he had been faced with "disdain and surprise."[132] One of Mach's earliest historically motivated criticisms of the concepts of mechanics, a brief article on the definition of mass written in 1867, was rejected by Poggendorff for publication in the *Annalen*, much to Mach's dismay. As a consequence, he long remained hesitant to share his more elaborate historical work with fellow physicists, such as his studies of the law of inertia: if he had already upset his colleagues by "so simple and clear a matter," he asked himself, "what could I expect in a more difficult question?"[133]

Mach ultimately acknowledged that his historical approach to physics, although resonating widely in various intellectual contexts, had received little practical following within the disciplines that he had sought to connect. During the final stages of his career, he even distanced himself from the discipline of physics. His insistence on the historical conditioning and impermanence of physical theories had been heavily criticized, especially by leading German physicist Max Planck.[134] In the 1912 edition of *The Development of Mechanics*, Mach observed that criticism of his work has been "numerous and of all kinds: historians, philosophers, metaphysicians, logicians, educators, mathematicians, and physicists." Subsequently, he dissociated himself from these disciplinary specializations: "I can make no pretence to any of these qualifications in any superior degree." Accordingly, he positioned himself in between the professional disciplines of history and physics, as "a man who had a most lively and [naïve] interest in understanding the growth of physical ideas."[135]

## CONCLUSION

I have argued that Mach valued historical methods as a tool for the physicist. By examining Mach's concrete historical research practices, I have been able to lay out the components of this tool. Mach's historical methods included the reading, ordering, and comparison of historical sources, as well as the

132. Mach, *History and Root* (ref. 15), 76.

133. Ibid., 80.

134. Daan Wegener, "De-Anthropomorphizing Energy and Energy Conservation: The Case of Max Planck and Ernst Mach," *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 41, no. 2 (2010): 146–59.

135. Mach, *Mechanics* (ref. 14), 326.

historical-philological method of source criticism. Admittedly, Mach's source criticism was less thorough than that of nineteenth-century German historians, including Wohlwill. Indeed, while Mach championed the method of source criticism, he relied primarily on the critical work performed by others. Mach's limited critical performance becomes comprehensible when appreciating that his integration of historiography and physics was asymmetrical: he reasoned from the perspective of the physicist, and by no means aimed to become part of the disciplinary community of historians. His view on the past was unapologetically shaped by the present, in particular by the conceptual problems that he perceived to haunt the physics of his day.

I began this article by referring to recent calls for a convergence of historical and natural-scientific knowledge. What can those aspiring to combine historical and natural-scientific today learn from Mach's successes, as well as from the obstacles that he encountered while seeking to integrate different disciplinary knowledges?

First, this study has demonstrated that historical and natural-scientific disciplines can complement and reinforce one another not just by exchanging insights about shared problems and objects of research but also, at a more basic level, by exchanging methods used to produce those insights. I have shown that Mach was not the only prominent German-speaking researcher in his day to successfully use the source-critical method to study the natural world.[136] His historical approach to psychophysics was influenced by and resembled Helmholtz's, and the Viennese botanist Anton Kerner turned source criticism into an integral part of his natural research as well. Today, the source-critical method still plays important roles in natural-scientific research. In forensic science and medicine, source criticism forms a key aspect of assessing evidence.[137] Climate scientists, furthermore, engage in the critical evaluation of historical sources in the process of reconstructing a reliable historical record of temperature data. While scrutinizing the historical data obtained by local weather stations, they recover "whatever can be learned about the station's history, correcting for some kinds of changes, rejecting anomalous data points



136. Still further research is needed to determine if and how, in the decades around 1900, historical and natural-scientific inquiry were similarly combined outside of German-speaking contexts. It should thereby be taken into account that the historical-philological and natural-scientific disciplines were culturally and socially less close to one another in, for instance, Britain and France than in Austria and Germany.

137. Rens Bod, "A Comparative Framework for Studying the Histories of the Humanities and Science," *Isis* 106, no. 2 (2015): 367–77, on 375.

as likely errors, and so on."[138] As Paul Edwards explained, "building stable, reliable knowledge of climate change [entails] constantly unpacking, re-examining, and revising . . . historical evidence."[139] Especially when these recent examples of natural-scientific application of historical method are also taken into account, it becomes apparent that methods commonly associated with historical research can be fruitfully applied in the making of natural knowledge, even in times of disciplinary specialization and fragmentation.

The case of Mach has also indicated some of the intricacies of knowledge integration between disciplinary contexts. Mach's historical studies were widely read by physicists and made a transformative impact on the discipline in the beginning of the twentieth century. In that regard, his application of historical methods to physics was highly successful. To his own disappointment, however, his desired, hybrid mode of historical-physical inquiry never gained a foothold; Mach fashioned historical method as a tool for the physicist, but this tool was never widely adopted on a disciplinary level.

Many have portrayed disciplinary boundaries as obstacles that need to be overcome in order to integrate knowledge. Jürgen Renn, for example, has argued that the ongoing fragmentation of scientific knowledge into ever-more specialized disciplinary communities has hindered opportunities for knowledge integration in the context of present-day challenges.[140] Others, however, have emphasized the productive role of disciplinary structures in knowledge integration. Historian Julia Thomas and paleobiologists Mark Williams and Jan Zalasiewicz, for example, have argued that disciplinary structures actually provide robust frameworks in which the currently desired integration of human and natural knowledge in the Anthropocene can be established. "In the face of unprecedented challenges," they have asserted, "we need the rigor of established disciplines to ensure expertise and to assess evidence, but we also need these disciplines to be self-reflective and to engage with work not just in adjacent fields but in distant ones."[141]

From this perspective, it appears that Mach should have put a lot of effort into anchoring his approach in existing disciplinary structures. As we have seen, however, he chose a different strategy: Mach regarded disciplinary boundaries as obsolete and sought to break them down. In 1894, he even

138. Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, MA: The MIT Press, 2010), 302.

139. Ibid., 398.

140. Renn, *The Evolution of Knowledge* (ref. 1), 33.

141. Thomas et al., *The Anthropocene* (ref. 2), chap. 1.

predicted that disciplines would "gradually disappear."[142] Contrary to Mach's expectations, however, disciplinary structures have become only more important. For those currently attempting to integrate knowledge across disciplinary boundaries, therefore, it seems essential to achieve a different balance between the disciplinary and the interdisciplinary than did Mach.

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142. Mach, "On the Principle of Comparison in Physics" (ref. 67), 257–58.