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Strong Foundations: Petrus van Musschenbroek's Experimental Research on the Strength of Materials

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ABSTRACT

In this article, I discuss Petrus van Musschenbroek's research on the strength of materials in relation to his methodological views. In the latter, van Musschenbroek emphasizes the importance of repeating and varying experiments. This is related to his views on the complexity of nature, which play a role in his views on mathematics, laws of nature, causes, and experimental method. In each case, the construction of an (experimental) history is presented as a first step in experimental philosophy, necessary to deal with the complexity of nature. The experimental research on the strength of materials can likewise be seen as aimed at the construction of an (experimental) history. His experimental practice takes the form of a systematic variation of parameters and the performance of an extensive series of experiments on different kinds of substances. In his experimental reports, van Musschenbroek repeatedly points to the utility of his experimental results. This utilitarian attitude is typical for the experimental history literature as discussed by Klein. Van Musschenbroek himself also presents his work as an experimental history. However, unlike the examples discussed by Klein, van Musschenbroek's experimental history is characterized by a systematic experimental method. I argue that this method can be seen as an example of exploratory experimentation in Steinle's sense. Finally, I suggest that with its emphasis on the nature and properties of specific materials, it could be fruitful to read van Musschenbroek's experimental history in light of the emergence of engineering as a discipline in the eighteenth century.

KEY WORDS: experimental philosophy, experimental history, material strength, exploratory experimentation, engineering

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The following abbreviation is used: MS LUL BPL, Manuscript Leiden University Library Bibliotheca Publica Latina.

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INTRODUCTION

In this article, I discuss Petrus van Musschenbroek's (1692–1761) research on the strength of materials in relation to his philosophy and practice of experimentation.[1] In the current literature, van Musschenbroek is mentioned primarily for his discovery of the Leiden jar and for his role in the spread of Newton's ideas on the Continent.[2] In his own time, van Musschenbroek was a well-known natural philosopher and a celebrated experimentalist.[3] This article aims to shed light on van Musschenbroek's philosophy and practice of experimentation. More specifically, it analyzes a somewhat neglected part of van Musschenbroek's work: his research on the strength of materials.

Van Musschenbroek came from a well-known family of instrument makers. The van Musschenbroek workshop had been established by Adriaen Joosten van Musschenbroek (1590–1663), who moved from Rotterdam to Leiden in 1610 and registered in the city as "brass founder."[4] His grandson, Samuel van Musschenbroek (1640–1681), would shift the activities of the workshop toward the production of scientific instruments.[5] After Samuel's death, the workshop

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1. Throughout this article, I use the terms "strength of materials" and "cohesion" interchangeably, as the terms "corporum firmitas," "cohaesio," and "cohaerentia" were likewise used interchangeably by van Musschenbroek himself. When citing primary literature, I will also use the term "coherence" when the term "cohaerentia" is used in Latin, to differentiate it from the use of the term "cohaesio" (translated as "cohesion"). In what follows, all translations of van Musschenbroek citations (be they Latin or Dutch) are my own.

2. For the Leiden jar, see Pieter Present [Beck], "Petrus van Musschenbroek (1692–1761) and the Early Leiden Jar: A Discussion of the Neglected Manuscripts," *History of Science* 60, no. 1 (2022): 103–29. For discussions of van Musschenbroek in relation to Newton's thought, see (among others): Kees (Cornelis) de Pater, "'The Wisest Man to Whom This Earth Has as Yet Given Birth': Petrus van Musschenbroek and the Limits of Newtonianism," in *Newton and the Netherlands*, ed. Eric Jorink and Ad Maas (Amsterdam: Leiden University Press, 2012), 139–53, and Steffen Ducheyne, "Petrus van Musschenbroek and Newton's 'Vera Stabilisque Philosophandi Methodus,'" *Berichte Zur Wissenschaftsgeschichte* 38, no. 4 (2015): 279–304.

3. For a general discussion of van Musschenbroek's philosophical views and his experimental research, see Cornelis de Pater, *Petrus van Musschenbroek (1692–1761), Een Newtoniaans Natuuronderzoeker* (Utrecht: Elinkwijk, 1979) and Pieter Present [Beck], *Learning in the World: Petrus van Musschenbroek (1692–1761) and '(Newtonian) Experimental Philosophy'* (Brussel: VUBPress, 2019). A discussion of van Musschenbroek's natural philosophy in relation to his views on physics (*physica*) is provided in Steffen Ducheyne, "Petrus van Musschenbroek (1692–1761) on the Scope of Physica and Its Place within Philosophia," *Asclepio* 68, no. 1 (2016): 123. doi:10.3989/asclepio.2016.02

4. Peter de Clercq, *At the Sign of the Oriental Lamp: The Musschenbroek Workshop in Leiden, 1660–1750* (Rotterdam: Erasmus Publishing, 1997), 31.

5. Ibid., 33–37.

was taken over by his younger brother (and Petrus's father), Johan Joosten van Musschenbroek (1660–1707).[6] After Johan Joosten's death, the workshop was taken over by his oldest son, Jan van Musschenbroek (1687–1748).[7] Petrus, the youngest son, was destined for an academic career.

Van Musschenbroek obtained his doctorate in medicine on November 12, 1715, with a dissertation titled "On the Presence of Air in Animal Fluids."[8] His supervisors included Herman Boerhaave (1668–1738). We will return to the figure of Boerhaave and his influence on van Musschenbroek's views on experimental philosophy. In 1719, van Musschenbroek was offered a professorship in mathematics and philosophy at the university of Duisburg. In 1723, he moved to Utrecht, where he had received a professorship in philosophy and medicine. From 1740 until the end of his life, van Musschenbroek held a professorship in mathematics and philosophy at his alma mater, Leiden University.[9]

Van Musschenbroek's activities as a professor materialized in the form of several textbooks, the first of which appeared in 1726.[10] Van Musschenbroek would keep expanding and revising this basic text, leading to the publication of several editions of the textbook under different titles. The textbooks were translated into English, French, and German, among other languages.[11]

Van Musschenbroek was also well known for his experimental work. In 1729, he published his *Physicae experimentales, et geometricae*, which contained the results of his research on magnetism, capillarity, and the strength of materials.[12] The experiments on magnetism and capillarity have been discussed in the foundational work of Kees de Pater.[13] Van Musschenbroek's later

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[6] Ibid., 36.

[7] Ibid., 41.

[8] Petrus van Musschenbroek, *Disputatio medica inauguralis de aëris praesentia in humoribus animalibus* (Leiden: Apud S. Luchtmans, 1715). For a discussion of this dissertation, see de Pater, *Petrus van Musschenbroek* (n.3), 31–32.

[9] De Pater, *Petrus van Musschenbroek* (n.3), 24–28.

[10] Petrus van Musschenbroek, *Epitome elementorum physico-mathematicorum conscripta in usus academicos* (Leiden: Samuel Lugtmans, 1726).

[11] An overview of these translations can be found in the extensive bibliography of van Musschenbroek's published works included in de Pater, *Petrus van Musschenbroek* (n.3), 349–60.

[12] Petrus van Musschenbroek, *Physicae experimentales, et geometricae, de magnete, tuborum capillarium vitreorumque speculorum attractione, magnitudine terrae, cohaerentia corporum firmorum dissertationes: Ut et ephemerides meteorologicae Ultrajectinae* (Leiden: Samuel Luchtmans, 1729).

[13] De Pater, *Petrus van Musschenbroek* (n.3), 122–291. De Pater also discusses the broader reception of van Musschenbroek's experimental work on these subjects.

experimental work on electricity has received extensive scholarly attention.[14] His experimental work on the strength of materials, however, has been somewhat neglected in the literature.[15] The first aim of this paper is to remedy this neglect by providing a description and contextualization of van Musschenbroek's experimental research on this subject.

The second aim of this paper is to relate van Musschenbroek's experimental practice regarding the strength of materials to his philosophical views on the nature and role of experiments in natural philosophy. As mentioned, van Musschenbroek has been discussed in the literature on Newtonianism primarily for his role in the spread of Newton's idea's. More recently, Steffen Ducheyne has provided a more nuanced view of van Musschenbroek's methodological views and their relation to those of Newton, more specifically showing how van Musschenbroek's methodological views deviated from those of Newton in important respects.[16] In the literature, van Musschenbroek's emphasis on the foundational role of experiments in natural philosophy has been noted, but a more elaborate analysis of his views on the epistemic role of

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[14] John L. Heilbron, *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics* (Berkeley/Los Angeles/London: University of California Press, 1979), 313–14; Cibelle Celestino Silva and Peter Heering, "Re-Examining the Early History of the Leiden Jar: Stabilization and Variation in Transforming a Phenomenon into a Fact," *History of Science* 56, no. 3 (2018): 314–52; Present [Beck], *Learning in the World* (n.3), 151–78.

[15] This experimental work has been treated in works dealing with the history of structural mechanics and the strength of materials specifically, or has been discussed in more historical articles in engineering journals. See, for example, Clifford Truesdell, *The Rational Mechanics of Flexible or Elastic Bodies, 1638–1788: Introduction to Leonhardi Euleri Opera Omnia Vol. X et XI Seriei Secundae* (Basel: Birkhäuser, 1960), 150–53; Edoardo Benvenuto, *An Introduction to the History of Structural Mechanics. Part I: Statics and Resistance of Solids* (New York: Springer-Verlag, 1991), 280–84; Stephen Timoshenko, *History of Strength of Materials: With a Brief Account of the History of Theory of Elasticity and Theory of Structures* (New York: Dover Publications, 1983), 54–55; and more recently Luis A. Godoy and Isaac Elishakoff, "The Experimental Contribution of Petrus Van Musschenbroek to the Discovery of a Buckling Formula in the Early 18th Century," *International Journal of Structural Stability and Dynamics* 20, no. 5 (2020): 2050063. doi.org/10.1142/S0219455420500637. I do not mean to minimize the importance of these studies. However, the specific focus on van Musschenbroek's experimental work as an episode in the history of structural mechanics means that the analysis of his experiments provided in these works differs from the kind of analyses found in the general historiography of science.

[16] Ducheyne, "Petrus van Musschenbroek" (n.2). Ducheyne has also pointed to other influences on van Musschenbroek's methodological thought, for example the work of Bernard Nieuwentijt: Steffen Ducheyne, "Constraining (Mathematical) Imagination by Experience: Nieuwentijt and van Musschenbroek on the Abuses of Mathematics," *Synthese* 196 (2019): 3595–3613. doi.org/10.1007/s11229-017-1392-1

experiments and how these views relate to his practice of experimenting is still wanting.

In my analysis, I will draw special attention to the role van Musschenbroek confers to so-called "experimental histories." Ursula Klein has recently drawn attention to the importance of this concept for the historiography of seventeenth- and eighteenth-century experimental sciences. The notion of an "experimental history" ultimately derives from Francis Bacon.[17] Due to his emphasis on the collection of many observations and experimental data and the need to avoid theoretical presuppositions when doing this, van Musschenbroek has in the earlier literature on Newtonianism been labeled as a "Baconian Newtonian."[18] More recently, Ducheyne has argued that the label "Baconian" is equally problematic to "Newtonian" in characterizing van Musschenbroek's methodological thought.[19] At the same time, Ducheyne concludes that van Musschenbroek's "empirico-mathematical project is in fact structurally closer to the way in which Bacon combined mathematics and empirical findings."[20] By focusing on van Musschenbroek's views on the construction and use of natural/experimental histories and comparing them to Klein's analysis of Boerhaave, I hope to provide a more fine-grained analysis of the elements of van Musschenbroek's thought that earned him the label "Baconian" in the earlier literature.[21] At the same time, by analyzing van Musschenbroek's philosophy and practice, I hope to contribute to the historiography on the notion and practice of experimental history as well.

My third and final aim here is to assess the place of van Musschenbroek's philosophy of experimentation and his research on the strength of materials within the broader intellectual developments taking place at the time.

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[17] Ursula Klein, "Experimental History and Herman Boerhaave's Chemistry of Plants," *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences* 34, no. 4 (2003): 533–67; Ursula Klein and Wolfgang Lefèvre, *Materials in Eighteenth-Century Science: A Historical Ontology* (Cambridge, MA: MIT Press, 2007), 22–24.

[18] See, for example, Robert E. Schofield, "An Evolutionary Taxonomy of Eighteenth-Century Newtonianisms," *Studies in Eighteenth-Century Culture* 7 (1978): 175–92, on 179–80.

[19] Ducheyne, "Petrus van Musschenbroek" (n.2), 290–91.

[20] Ibid., 294.

[21] Note that I do not aim to provide an explicit comparison between van Musschenbroek's views and the methodological views of Bacon. For a short list of some differences between van Musschenbroek and Bacon, see Ducheyne, "Petrus van Musschenbroek" (n.2), 290–91. Given that Herman Boerhaave was an important influence on van Musschenbroek, I will limit myself here to a comparison of van Musschenbroek's views on experimental history to those of Boerhaave (as analyzed by Klein).

The article is structured as follows. In section 1, I elaborate on the notion of "experimental history" and discuss the work done by Ursula Klein. In section 2, I provide a discussion of van Musschenbroek's methodological views, specifically those pertaining to the role of experiments and the construction of natural/experimental histories. Section 3 contains a discussion and analysis of van Musschenbroek's research on the strength of materials. In subsection 3.1, I discuss the research presented in van Musschenbroek's *Physicae experimentales* (1729). In subsection 3.2, I discuss one specific subset of later research performed by van Musschenbroek on the strength of materials, namely his research on the strength of alloys. In both subsections, I show how the research illustrates van Musschenbroek's philosophical views. I also show where and how the presentation of the research on strength of materials can be read as an example of an experimental history. The main difference between the works discussed by Klein and van Musschenbroek's experimental history is that van Musschenbroek's history was the result of systematic experimental research, whereas for Klein experimental history is characterized by the lack of such a methodic way of experimenting. Whereas for Klein there is a gap between experimental history and experimental philosophy, this gap is not present in van Musschenbroek's work. In the article's final section, I discuss the place of van Musschenbroek's philosophy of experimentation and his research on the strength of materials within the broader intellectual developments taking place at the time. More specifically, I suggest that van Musschenbroek's program of experimentally investigating the properties of *specific* types of substances and materials should be seen in the context of the emergence of engineering as a discipline in the eighteenth century.

1. EXPERIMENTAL HISTORY

In an article discussing Herman Boerhaave's *Elementa chemiae* (1732), Ursula Klein uses the concept of an "experimental history" to analyze Boerhaave's presentation of experiments on plants and plant materials.[22] The concept was not introduced by Klein as an analytical category but goes back to the work of Francis Bacon (1561–1626), who called for the creation of "experimental histories" as part of his methodological program. The notion was further used and developed in the work of Robert Boyle.[23] Klein argues that Boerhaave's

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[22] Ursula Klein, "Experimental History" (n.17).

[23] Ibid., 538–41.

presentation of plant-chemical experiments in the *Elementa chemiae* can be seen as an example of an experimental history. She also makes the broader claim that the commitment to the creation of experimental histories was shared by many European chemists of the mid–eighteenth century.[24]

"Experimental history," in the Baconian sense, is meant as a complement to natural history. Whereas natural history collected "matters of fact based on the observation of things and processes" as they are found in nature, experimental history provided "an inventory of extant operations or 'experiments' in the arts and crafts and in everyday life."[25] Examples of such inventories include the *Descriptions des arts et métiers* of the Académie Royale des Sciences and the Royal Society's work on a history of trades.[26] In the experimental philosophy of Bacon, Boyle, and others, there was no strict ontological distinction between the phenomena observed when nature is allowed to work freely, and artificial phenomena observed in the laboratory or the workplace. The latter therefore become informative for natural philosophy, and experimental histories thus complement natural histories.[27]

The business of experimental history was, however, not limited to passively observing and making an inventory of the works of artisans. It also involved the repetition of existing operations *and* "the extension of operational, artisanal knowledge by performing additional experiments."[28] This often had utilitarian aims. Klein refers to Boerhaave's praise of the usefulness of chemistry in his 1718 inaugural lecture and also shows how many of the plant-chemical experiments detailed in the *Elementa chemiae* involve the production of materials with medical or other uses.[29]

Klein argues that "experimental history" should be distinguished from "experimental philosophy." She cites a passage from Boyle's *Experimental History of Colours* (1664) where Boyle states that he did not present the

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[24] Ibid., 536–37. These claims are further developed and substantiated in Klein and Lefèvre, *Materials in Eighteenth-Century Science* (n.17), 21–30.

[25] Klein, "Experimental History" (n.17), 539.

[26] Ibid., 534. The interaction between artisans and natural philosophers in the early modern period has been an important topic in the historiography of science. For some recent examples, see Paola Bertucci, *Artisanal Enlightenment: Science and the Mechanical Arts in Old Regime France* (New Haven, CT: Yale University Press, 2017) and Wolfgang Lefèvre, *Minerva Meets Vulcan: Scientific and Technological Literature—1450–1750* (Cham: Springer Nature, 2021). Bertucci's work focuses specifically on the activities of the Académie Royale in this context.

[27] Ibid., 539–40.

[28] Ibid., 540.

[29] Ibid., 534–35, 561.

experiments in a methodical way, finding himself "unfit to speculate."[30] More generally, Klein sees two ways in which experimental history differs from experimental philosophy: "'Experimental history' then would differ from 'experimental philosophy,' first, by the absence of a clear-cut theoretical framework, and second, as a consequence, by the additional absence of a methodological way of experimenting."[31]

In the next section, I discuss van Musschenbroek's views on the nature and role of experimental histories in experimental philosophy. In section 3, I discuss van Musschenbroek's research on the strength of materials as an example of the construction of an experimental history. However, I also show how van Musschenbroek's research *did* involve a systematic way of experimenting.

At the same time, van Musschenbroek also reports surprising results and provides details on the behavior of specific materials, often without linking these to theoretical considerations. In most cases, van Musschenbroek comments on the utility of knowing these results. This utilitarian orientation becomes even more outspoken in his later research on the strength of different alloys. But in these cases as well, the experimental research itself was still characterized by a systematic way of experimenting.

2. THE METHOD OF EXPERIMENTAL PHILOSOPHY

2.1 The Use and Limits of Mathematics

The earliest exposition of van Musschenbroek's methodological views can be found in his oration "On the Certain Method of Experimental Philosophy (*De certa methodo philosophiae experimentalis*)."[32] He delivered this oration when he took up the position of professor of philosophy and mathematics at the university of Utrecht in 1723. The oration is explicitly presented as an outline of his methodological views.[33] Van Musschenbroek argues that we cannot

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[30] Boyle quoted in Klein, "Experimental History" (n.17), 540. This point is worked out further in Klein and Lefèvre, *Materials in Eighteenth-Century Science* (n.17), 23–24.

[31] Klein, "Experimental History" (n.17), 541.

[32] Petrus van Musschenbroek, *Oratio de certa methodo philosophiae experimentalis* (Utrecht: Guilielmum Vande Water, 1723).

[33] Van Musschenbroek, *Oratio de certa methodo* (n.32), 7. As an oration, the text also had a very rhetorical character. For an analysis of van Musschenbroek's orations from a rhetorical point of view, see Pieter Present [Beck], "'Following No Party But The Truth': Petrus Van Musschenbroek's Rhetorical Defence Of (Newtonian) Experimental Philosophy," *History of Universities* 33, no. 2 (2020): 143–74.

know the workings of nature through *a priori* reasoning. Only by means of experimentation, and by reasoning on the basis of these experiments, can we gain knowledge of nature.[34] Van Musschenbroek does not want to deny the role of mathematics in physics, but emphasizes that we should remain conscious of its limits.

When a mathematician is doing mathematics, he is working within his "pure science (*scientia pura*)," and his cognition consists in working with ideas about things "the nature of which he has formed himself [. . .] and which, being most simple, he conceives in one intuition."[35] This explains the certainty of mathematics. However, whereas in mathematics we are able to conceive a mathematical object in one intuition, this is not possible when we reason about objects in the outside world. When reasoning about bodies, we reason only on the basis of ideas representing certain attributes of those bodies. Therefore, unlike mathematics, where we can intuit a mathematical object at once, when we reason about an external object we "do not put the entire body before [our] mind's eye, but [only] a certain idea of this or that attribute."[36] We should therefore be conscious of the difference between the two cases: "[in the one case] one attribute of a composite thing is contemplated in an abstract meditation, [in the other] the nature of a most simple thing will be contemplated."[37] Reasoning mathematically about physical phenomena therefore does not guarantee that the certainty found in mathematical reasoning is transferred to physics:

> [W]e can reason correctly in the mathematical way starting from such an abstract idea, and it will be the most true reasoning, in so far as [*quatenus*] one contemplates an abstract property. If it would have been the sole [property] that the body had, there would have been no doubt left, but if it had several [properties], then doubt remains. Because it can happen in composite things, that several attributes, which exist together, and are inseparable from the things, are its [i.e., of the composite thing] nature, by which they could hinder, that a conclusion deduced from one of the two, would follow legitimately.[38]

We should therefore rid ourselves of the illusion that we are still reasoning mathematically when we are blindly applying mathematics to physics in cases

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[34] Van Musschenbroek, *Oratio de certa methodo* (n.32)., 10.

[35] Ibid., 23–24.

[36] Ibid., 24.

[37] Ibid., 24–25.

[38] Ibid., 24–25.

where such an application is not possible. In those cases, van Musschenbroek says, “we are abusing mathematics” (*mathesi abutimur*).[39] Van Musschenbroek refers to the *vis viva* controversy as an example in which only experiments were able to settle the matter, not pure mathematical reasoning. It was the experiments performed by ’s Gravesande that had clearly settled the issue.[40] Van Musschenbroek repeats his point on the foundational role of experiments in experimental physics, now explicitly using the concept of an “experimental history” (*historia experimentalis*):

> We see controversies between physico-geometers, which would not have existed, if mortals had first completed an experimental history before they completely lost themselves in their reasonings. Because that [experimental history] will then provide [their] reasoning with the first data, which always are, have been, and will remain completely true.[41]

The use of mathematics in physics is limited because the ideas we have of natural bodies are limited. Nature is more complex than the abstract ideas that we use in mathematical reasoning suggest. Next, we will see how the complexity of nature likewise played an important role in van Musschenbroek’s thinking on the laws of nature.

2.2 Laws of Nature

In his first textbook, van Musschenbroek provides the following definition of the term “law”:

“By ‘law’ we mean the rule, according to which God wanted that when bodies [are placed] in such circumstances, those kind of phenomena would occur in the most constant manner.”[42] The term “phenomenon” had itself been defined in the preceding paragraphs, and is to be understood as any sensory observation.[43] Given this definition of phenomena, van Musschenbroek can be seen to understand laws in terms of empirical regularities.

In the paragraph immediately following this definition, he incorporates and elaborates on the points made in his 1723 oration. The laws of nature can be

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[39] Ibid., 27.

[40] Ibid., 27–28.

[41] Ibid., 28.

[42] Van Musschenbroek, *Epitome* (n.10), 3.

[43] “We call ‘phenomena’ all locations, actions, and changes of bodies, which we observe with either one, or with multiple senses. Therefore, they do not differ from what is observed by the senses” (ibid., 2–3).

discovered only through sensory observation. Because of their constant character, knowledge of these laws allows us to foresee events in the future. This is illustrated with the example of a wedge: if we see a wedge splitting a piece of wood today, we can expect the same kind of wedge to be able to split a similar piece of wood tomorrow.[44] As in the oration discussed above, van Musschenbroek again stresses the importance of compiling a history (*historia*) of data, now positing it explicitly as a prerequisite for establishing the universality of laws:

> However, we know laws to be universal, when we have experienced that the same [laws] obtain in all bodies. From which it is clear, that these [laws] cannot be suddenly established, but only after the history of all phenomena has been completed. Thus, we will be able to posit as a universal law that all bodies are acted upon by gravity, if we will have found gravity in all bodies of the universe.[45]

In 1734, a new edition of the textbook was published under the title *Elementa physicae*. The paragraph on laws was heavily reworked:

> All bodies move according to certain laws or rules, whatever be the cause moving [them]. Thus the motions of the planets are governed by certain laws; plants and animals are produced from their seed by a constant and always identical law, [and] bodies that collide with one another, act on one another following inviolable rules, either by taking up forces or transferring them.[46]

In the next edition (1741), another example of a law is now added to that of the wedge: when we see that a mustard seed sown in fertile ground produces rich crops this year, we can expect it to do the same next year in similar circumstances.[47] The examples of animals and plants show that van Musschenbroek's focus was no longer exclusively on the laws of motion but also on the laws governing the plant and animal kingdom. As in the previous editions, van Musschenbroek discusses the vast scope of physics and the need to make numerous empirical observations before one is able to put forward laws. He says that "[t]his should be done [. . .] because nature abounds in such

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[44] Ibid., 3.

[45] Ibid., 4.

[46] Petrus van Musschenbroek, *Elementa physicae conscripta in usus academicos* (Leiden: Samuel Luchtmans, 1734), 3.

[47] Petrus van Musschenbroek, *Elementa physicae conscripta in usus academicos*, 2nd ed. (Leiden: Samuel Luchtmans, 1741), 4.

variety: we should not confirm [laws to be] general laws, [when] they are only singular [laws]."[48]

The Dutch 1736 translation of the textbook, written by van Musschenbroek himself, provides a further discussion of the distinction between "general laws" and "singular laws." Van Musschenbroek again emphasizes the need to investigate many kinds of bodies before putting forward general laws. He refers to the amount of species found in Conrad Gesner's (1516–1565) work, and to the various kinds of minerals listed in John Woodward's (1665–1728) works as examples of the vastness of nature.[49] We should take care not to think too quickly to have found general laws because experience shows "that there are many special laws (*byzondere wetten*), and less general [ones]."[50] As an example, van Musscenbroek mentions that it seems to be a general law that animals are born out of eggs. However, when the eggs of bloodless animals hatch, a worm appears that first changes into a pupa and only then changes into a fly. These are examples of "special laws, which one can only learn through experience, by investigating every species separately."[51]

Van Musschenbroek rewrote the paragraphs on laws of nature for each new edition of his textbook.[52] The emphasis on the variety of nature and the need to collect many observations before claiming to have found a law of nature remained a constant factor.

Van Musschenbroek's warnings against hasty generalizations are often coupled with warnings against searching for causes. In the 1734 textbook, he writes that "we do not know the cause and reason of these laws."[53] In the 1736 Dutch translation, this is made more specific with an example. He writes that he would rather confess his ignorance than "to claim with vanity already to know how from a mustard seed an entire plant grows, and [to claim] that this happened through the mechanical powers of the seed itself."[54] This example makes clear that van Musschenbroek not only refers to the causes of the laws of nature but also to the causes underlying natural phenomena. However, at

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[48] Van Musschenbroek, *Elementa physicae* (1734) (n.46), 5.

[49] Petrus van Musschenbroek, *Beginselen der natuurkunde beschreeven ten dienste der landgenooten* (Leiden: Samuel Luchtmans, 1736), 8.

[50] Ibid., 8–9.

[51] Ibid., 9.

[52] For an elaborate overview and analysis of these changes, see Steffen Ducheyne and Pieter Present [Beck], "Pieter van Musschenbroek on Laws of Nature," *The British Journal for the History of Science* 50, no. 4 (2017): 637–56.

[53] Van Musschenbroek, *Elementa Physicae* (1734) (n.46), 4–5.

[54] Van Musschenbroek, *Beginselen* (n.49), 7.

several places in his oeuvre, van Musschenbroek included the search for causes in his definition of physics. In the next subsection, I will analyze this tension in van Musschenbroek's work and how it relates to his views on the role of natural and experimental histories.

2.3 The Search for Causes and the Role of (Experimental) Histories

In order to put the apparent tension in clear view, let us return to the 1723 oration on the method of experimental physics. In the beginning of the oration, van Musschenbroek provided a definition of "experimental physics." In this definition, he included the search for causes (*causas indagare*) as a part of the endeavor of experimental physics.[55]

Despite the inclusion of the search for causes in the definition of experimental physics, in the same oration van Musschenbroek also says such things as, "Whatever we have said so far only pertains to observations of effects, about their causes I am brought to silence."[56] Therefore, van Musschenbroek says that he no longer wants to deal with "the injuries, troubles, and errors, which [philosophical] systems, and the uprooting of causes, have brought into physics."[57]

On the other hand, in the preface to the second edition of his Dutch textbook (1739), van Musschenbroek mentions that the limited nature of our knowledge of causes has led some "to neglect or skip the search for causes" and to focus instead on looking for proportions between phenomena on the basis of mathematics.[58] Given the aforementioned remarks, one would expect him to rejoice about this, as it is exactly what he had been arguing for. Surprisingly, van Musschenbroek laments the neglect of the search for causes. The search for regularities "is not enough to bring physics to its perfection, because we also need to know the causes."[59]

In the 1741 edition of the textbook, van Musschenbroek introduces the concept of a "true cause" (*vera causa*) in his discussion of Newton's *regulae*

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[55] Van Musschenbroek, *Oratio de certa methodo* (n.32), 9.

[56] Ibid., 33.

[57] Ibid., 40.

[58] Van Musschenbroek, *Beginsels*, unnumbered preface. Echoing Bacon, van Musschenbroek adds that in order to find causes, we need to perform experiments "by which means one can open Nature with violence as it were, and to force one's way into her secrets" (Ibid.). The discipline of chemistry is according to van Musschenbroek the most exemplary practice in this regard (Ibid).

[59] Petrus van Musschenbroek, *Beginsels der natuurkunde beschreeven ten dienste der landgenooten* (Leiden: Samuel Luchtmans, 1739), unnumbered preface.

philosophandi and provides explicit criteria that allow one to determine whether or not the true cause of an effect has been found.[60] At this point, one might begin to wonder why van Musschenbroek so vehemently attacked the search for causes in the passages given at the beginning of this section and why he seemed to take such a strong agnostic stance toward them. If, as we have seen, causes *can* be found, and if we also have clear criteria that allow us to ascertain whether or not a supposed cause is a real cause, why does van Musschenbroek express such reservations toward the search for causes in natural philosophy?

Without going into details, we can say that van Musschenbroek's attitude toward the search for causes should be seen as moderately sceptical, not as a form of full-blown causal agnosticism. He does believe that it is possible to discover the true cause of a certain phenomenon and even provides explicit criteria to identify these causes. However, the search for causes according to him often leads people to feign hypotheses, which in turn leads to useless controversies among philosophers. It is therefore much better to confess one's ignorance rather than be tempted to put forward causes that have not been demonstrated to be "true causes" by means of observations and experiments.[61]

In one of van Musschenbroek's manuscripts, we find a passage that provides some insight on the way he conceptualized the relationship between the search for causes and the search for laws:

> After the physicist has collected the phenomena of diverse bodies through diligent observation, the mechanic reduces the collected [phenomena] to an order, by dividing them in their kinds and classes. While occupied in these matters he sees that several [properties] are common to all or several bodies; others are special [properties], which obtain only in a few bodies. Those [properties] which are common he calls *laws* and he concludes that whenever a body is affected following common conditions, that [body] necessarily changes following the law which he had learned and established by means of observations. Next, he extends these laws to similar [bodies]. Having proceeded up to this point with the most cautious reasoning, he starts to look for causes and the reason for why these laws obtain. If he will have been able

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[60] For a discussion of van Musschenbroek's notion of "true causes," see Present [Beck], *Learning in the World* (n.3), 71–76.

[61] For a more elaborate discussion of van Musschenbroek's views on causes, see Present [Beck], *Learning in the World* (n.3), 69–80.

> to penetrate into these things, he is called a physico-mechanicus, and he arrives at the goal to which all philosophers have always aimed. However, one approaches causes last of all things.[62]

Van Musschenbroek gives two reasons why causes should be looked for "last of all things." The first is that causes are hidden from us by God. Thus, they can be found only after hard work, and are often sought for in vain. The search for causes therefore does not give rise to useful results but aims only at satisfying our curiosity (which van Musschenbroek implicitly seems to regard as an impious attitude).[63]

In the last edition of his textbook, van Musschenbroek added the following paragraph:

> Knowledge (*cognitio*) is threefold. *History* (*historia*) is the name given [to the knowledge] which consists in the knowledge of bodies, and the appearances observed in them. This [knowledge] is primary, simple, certain, and the basis of physics. *Philosophy* is the second [kind of knowledge], when the causes of appearances are discovered, and when it is demonstrated which and how they are. *Mathematics* is the third [kind of knowledge], when the magnitudes of the appearances and causes are considered geometrically, and the things which follow from them, are collected. This is called into use last, and by means of this we can attain the highest degree of knowledge.[64]

In this paragraph, the search for causes precedes the search for (geometric) regularities. This not only contradicts the order found in the manuscript under discussion but also sits uneasily with the passages on laws in the same textbook, and the statement (again in the 1762 textbook) that causes cannot always be discovered. The passage does clearly show, however, that van Musschenbroek remained committed to the idea that the collection of observations in a *historia* should be the first and primary step in natural philosophy.

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[62] Van Musschenbroek, Manuscript Leiden University Library (henceforth LUL) Bibliotheca Publica Latina (henceforth BPL), item 240, part 12 (henceforth 240.12), fol. 335^{r-v}. Note that van Musschenbroek writes that after having discovered a certain law, the mechanic "starts to look for the causes and reason why these laws obtain." As we have seen, in the 1741 edition of his textbook van Musschenbroek stated explicitly that "we do not know the cause and reason of these laws" (van Musschenbroek, *Elementa physicae* (1741) (n.47), 4.

[63] Van Musschenbroek, MS LUL BPL 240.12, fol. 335^{v}.

[64] Van Musschenbroek, *Introductio ad philosophiam naturalem* (Leiden: Sam. et Joh. Luchtmans), Vol. 1, 11.

2.4 How to Perform Experimental Research

In 1730, a year after the publication of *Physicae experimentales*, van Musschenbroek delivered an oration titled "On the Method of Performing Physical Experiments" (*Oratio de methodo instituendi experimenta physica*).[65] Van Musschenbroek begins by painting the portrait of the ideal experimentalist. Experimentalists should not only be well learned and dexterous but should also have a sharp mind, including "an almost divine sagacity to distinguish the phenomena that arise by certain circumstances accompanying the experiment, from those that would have arisen, if the experiment would have been performed in another way or on another occasion."[66] This remark points to a central point in van Musschenbroek's thinking on experiments: the fact that in any experiment a complex array of variables is at play. This idea informs many of the points made by van Musschenbroek during the oration. Even before performing the experiments, steps should be made to take this fact into account. The experimenter should accurately describe the circumstances in which the experiment is being made, such as the location, date, time, temperature, air pressure, and so on.[67]

As examples of the importance of noting down the region in which the experiments were made, van Musschenbroek refers to variations in the oscillation of pendula of equal weight and length, and the inclination of a magnetic needle depending on the region of the world.[68] This information should be noted because before doing experiments we do not know the effect of these variables on the phenomena we are investigating.[69]

Later in the oration, van Musschenbroek also states that when one is investigating an unknown substance, one should take note of where it comes from and how it was collected.[70] In his personal copy, he added a note saying that this is important to know because even substances bearing the same name have different properties depending on the region where they come from and

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[65] The text of the oration was published a year later as Petrus van Musschenbroek, "Oratio de methodo instituendi experimenta physica" in *Tentamina experimentorum naturalium captorum in academia del cimento* (Leiden: Joan. et Herm. Verbeek, 1731), 1–48. For a detailed discussion of the contents of this oration, see Present [Beck], *Learning in the World* (n.3), 81–92.

[66] Van Musschenbroek, "Oratio de methodo instituendi" (n.65), 10.

[67] Ibid., 14.

[68] Ibid., 15.

[69] Ibid., 15.

[70] Ibid., 31.

therefore give rise to different effects.[71] We will see that this plays an important role in van Musschenbroek's later research on the strength of alloys.

The experiment itself should be repeated several times and in various ways. This can be understood as analogous to the demand of noting down the circumstances and reflecting on the parts of the experimental set-up and the possible disturbances at play in the experiment. This is confirmed by the fact that van Musschenbroek says that one should repeat experiments in different times of the year and in different weather conditions.[72] The experiment should also be repeated in different places and regions of the world.[73] Quantitative variations should likewise be introduced.[74] By varying the experimental set-up and the experimental circumstances in this way, one can gain knowledge of as many relevant variables as possible.

In the oration, van Musschenbroek also provides a practical counterpart to the views on causes discussed above. As we have seen, his cautious attitude toward the identification of causes was linked to an emphasis on the complexity of nature. When doing an experiment, this implies that one must be aware of the many variables at play. In his personal copy, van Musschenbroek made the following addition to the text of the oration: "Experiments are made amidst thousands of concurring causes, [and] if one of them is not taken into consideration, or not noted down, the truth will not let herself be discovered."[75]

Van Musschenbroek not only emphasizes that nature in general is heterogeneous but in the same oration warns that bodies that look like a homogeneous whole might in fact be composed of different kinds of substances. It is therefore necessary to analyze these bodies by chemical means.[76] Van Musschenbroek gives an elaborate overview of the different chemical methods used to further break down bodies into their constituent substances. This should be done as thoroughly as possible, until one ends up with substances that can be broken down no further. These are the so-called "simples." Van Musschenbroek does not regard these as ultimate elements but rather as operational simples: substances that cannot be analyzed further given the state of the art in chemistry.[77]

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71. Van Musschenbroek, MS LUL BPL 240.59 (n.62), marginal note on p. 31.
72. Van Musschenbroek, "Oratio de methodo instituendi" (n.65), 27.
73. Ibid., 29.
74. Ibid.
75. Van Musschenbroek, MS LUL BPL 240.59 (n.62), 39.
76. Van Musschenbroek, "Oratio de methodo instituendi" (n.65), 35–36.
77. Ibid., 39–40.

Once these simple substances are obtained, they should be combined with each other during the synthetic part of the investigation. All (or at least as much as possible) combinations should be made, and all the phenomena observed during this process should be noted as closely as possible. Combining two "simples" can result in a more complex body. This new body should again be combined with all relevant simples and other complex bodies made from two bodies. After each step, new bodies of increasing complexity should be combined with the relevant simples as well as with all the bodies of lesser complexity formed during previous steps of the investigation. Van Musschenbroek is aware this means the task is endless. Without providing the details of his calculation, he states that his method would entail that ten simple bodies give rise to three million possible mixtures. He also emphasizes the need to vary the circumstances in which substances are combined, for example by not only combining them in the open air but also in a vacuum.[78] A bit further in the oration, he explicitly describes this synthetic activity and the observations made and recorded during it as the construction of a history:

> All phenomena which are collected in this way, will have to be ordered in their classes, those, which are common to all, are to be put separately, distinct from singular [properties]: If however in these or others a magnitude should hold, so that they could be compared with one another in turn, they become an object for a mathematician, who by acquiring new data, can enlarge them with his demonstrations, and elucidate [them], and he will come closer to the determination of the causes, whether general or singular, and their magnitudes and proportions.[79]

To summarize, we have seen how in different contexts van Musschenbroek emphasizes the necessity of compiling a *history* before making theoretical claims about laws or causes. This was linked to his emphasis on the variety of nature. A similar emphasis on the specificity of individual bodies and a related mistrust of speculation can be found in Boerhaave's work.[80]

Van Musschenbroek provides no explicit remarks on the relationship between natural history and experimental history. In several instances he uses the unqualified term *historia*. As we have seen, in post-Baconian experimental philosophy, the distinction between the experimental/artificial and the natural

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[78] Ibid., 40–42.

[79] Ibid., 44.

[80] See Klein, "Experimental History" (n.17), 549.

became epistemically irrelevant. Experimental histories are as much a source of information on nature as natural histories are.

Although the construction of a *history* for van Musschenbroek clearly has an epistemic function and is the first step that should be taken in experimental philosophy, he does emphasize the need to separate the collection of data and facts in histories from the construction of theories on the basis of these data. In the introduction to the 1748 edition of his textbook, van Musschenbroek refers to the experimental research on electricity he performed years before.[81] He tells his readers he has not described all these experiments in the textbook:

> It seemed proper to select some experiments from the ones conducted by us, [namely] those which according to my judgment were suitable for these Institutions, and could be rendered in some form of method: a lot of others, which I have not yet been able to investigate in every part, and not from all accompanying circumstances, have been left for a future time. I would rather give a history of experiments, than a theory.[82]

This passage contrasts in an interesting way with the passage from Boyle cited by Klein. There, Boyle stated that he refrained from "a methodical way of delivering [his experiments]" due to the lack of a theoretical framework.[83] In the passage cited above, van Musschenbroek likewise states that he does not want to provide a theory regarding electrical phenomena, but prefers to offer a history of experiments. But unlike Boyle, he does not refrain from presenting his experiments in a methodical way. In her article, Klein goes further than Boyle's statement on the *presentation* of experiments and also states that experimental history is characterized "by the additional absence of a methodological *way of experimenting*."[84] In this section, we have seen how van Musschenbroek did suggest a methodic way of experimenting that could be followed to construct an experimental history. In the next section, we will see how this was put into practice in his research on the strength of materials.

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[81] It was during this research that he discovered the Leiden jar. For the Leiden jar see, Present [Beck], "Petrus van Musschenbroek" (n.2). For van Musschenbroek's research on electricity, see Present [Beck], *Learning in the World* (n.3), 151–78.

[82] Petrus van Musschenbroek, *Institutiones physicae conscriptae in usus academicos* (Leiden: Samuel Luchtmans et filius, 1748), 2.

[83] Klein, "Experimental History" (n.17), 540–41.

[84] Ibid., 541 (emphasis added).

3. VAN MUSSCHENBROEK'S RESEARCH ON THE STRENGTH OF MATERIALS

3.1 *Physicae Experimentales et Geometricae* (1729)

The earliest account of van Musschenbroek's research on the strength of materials is found in his *Physicae experimentales et geometricae* (1729). The section on cohesion is generally regarded as the first systematic experimental treatment of the topic.[85] Before van Musschenbroek, the topic had been treated in primarily an abstract, mathematical manner. We will see how van Musschenbroek himself, in line with his views on mathematics discussed above, pointed to the limitations of this purely mathematical treatment of the problem of cohesion.

At the beginning of the section on the strength of materials, van Musschenbroek provides the following definition of the subject:

> By "coherence," "strength" or "resistance" of solids we mean the force of bigger bodies by which their parts, connected in whatever way and by whatever cause, resist being separated or broken, so that these [parts] cannot be moved away from each other by the same forces which could just move them, or separate them if they had been only put on top of each other, but a bigger force is needed [for that].[86]

He then lists different ways in which two separate bodies can be made to cohere. This can happen by means of external pressure, magnetism or another attractive force, cold, heat, or by using a certain (semi-)fluid such as glue, by mixing certain chemicals, and by means of nails.[87] In order to explain these different ways of connecting bodies, van Musschenbroek continues, it is necessary to "look for the universal cause of coherence, or, if there are several, for all of them."[88] This leads to the following question: "Let us thus begin with the foundations of things, and investigate which cause makes that two elements (the smallest and ultimate corpuscles) cohere with each other, and compose some united molecule."[89]

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[85] Truesdell, *The Rational Mechanics* (n.15), 150–53; Benvenuto, *An Introduction* (n.15), 280–84; Timoshenko, *History of Strength of Materials* (n.15), 54–55.

[86] Van Musschenbroek, *Physicae experimentales* (n.12), 431.

[87] Ibid., 432–37.

[88] Ibid., 437.

[89] Ibid., 437.

The cause we are looking for, van Musschenbroek argues, is a certain type of force (*vis*), which is either external or internal to the elements.[90] Van Musschenbroek refers to several experiments that demonstrate it cannot be an external force and therefore concludes it must be an internal one.[91] Like gravity, he conceives this force as a law of nature put into bodies by God.[92] By explaining cohesion in terms of an internal force, van Musschenbroek follows in Newton's footsteps, who in Query 31 of his *Opticks* had asked: "Have not the small Particles of Bodies certain Powers, Virtues or Forces, by which they act at a distance."[93] Cohesion had been one of the phenomena that according to Newton could be explained by means of such forces, and according to him it was "the Business of experimental Philosophy to find them out"[94] I will return in section 4 to this Newtonian aspect of van Musschenbroek's research on the strength of materials.

Van Musschenbroek described his research into cohesion as a search for laws. Knowing these laws, he said, would be very useful, in contrast with the useless search for causes.[95] However, the search for the laws of cohesion had been neglected in favor of such a fruitless search. Therefore, van Musschenbroek says: "[I]n what follows, we will abstain from these things [i.e., looking for causes], and we will only put effort into discovering the laws of coherence."[96] He then provides an overview of the different ways in which bodies that cohere can be investigated.[97]

The first way is by applying a pulling force along the direction of the length of the body (cf. "Fig. 1" in Fig. 1). The force by which a body resists being broken by such a pulling force is called the "absolute coherence (*cohaerentia absoluta*)" of that body.[98] The other five ways involve applying the pulling force or the weight in different ways. Important to mention for the rest of the discussion is the second way, which involves fixing a body with one end in

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[90] Ibid., 438–44.

[91] Ibid., 444.

[92] Ibid., 451.

[93] Isaac Newton, *Opticks, or A Treatise of the Reflections, Refractions, Inflections & Colours of Light* (Mineola, NY: Dover Publications, 2012 [1730]), 375–76.

[94] Newton, *Opticks* (n.93), 394. For a discussion of Newton on cohesion and the reception of his views, see John S. Rowlinson, *Cohesion: A Scientific History of Intermolecular Forces* (Cambridge: Cambridge University Press, 2004), 8–82.

[95] Van Musschenbroek, *Physicae experimentales* (n.12), 465.

[96] Ibid., 465.

[97] Ibid., 465.

[98] Ibid., 466.

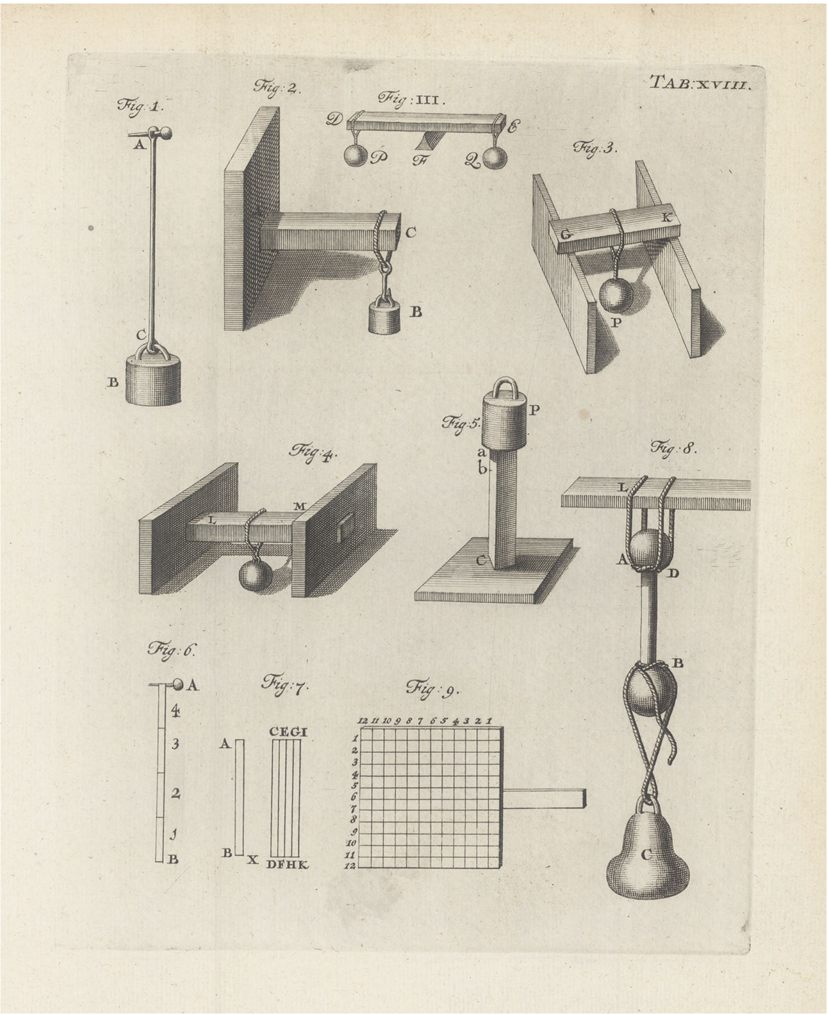

FIGURE 1. Six ways of investigating the coherence of bodies (Fig. 1–5 and Fig. III in van Musschenbroek, *Physicae experimentales* [n.12], Tab. 18). Scan of copy of *Physicae experimentales* in the collection of Ghent University Library. Digital reproduction provided by Ghent University Library.

a hole, and applying the force perpendicularly to the length of the body at the other end (cf. "Fig. 2" in Fig. 1). This is called the "relative coherence (*cohaerentia respectiva*)" of a body.[99]

As mentioned, in the literature on the history of the study of the strength of materials, the 1729 textbook by van Musschenbroek is generally taken to be the

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[99] Ibid., 525.

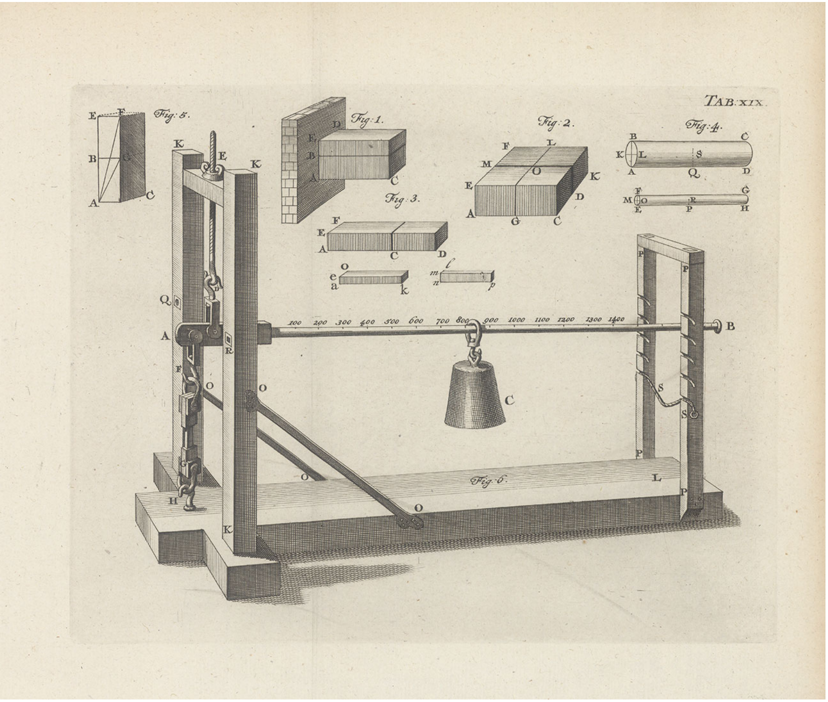

FIGURE 2. Van Musschenbroek's experimental set-up for experiments on absolute coherence (van Musschenbroek, *Physicae experimentales* [n.12], Tab. 19). Scan of copy of *Physicae experimentales* in the collection of Ghent University Library. Digital reproduction provided by Ghent University Library.

first comprehensive experimental study of the subject. With a few exceptions, before van Musschenbroek the study of the strength of materials was done in an *a priori* manner, by trying to derive general proportions on the basis of idealized models.

The first to provide such a treatment was Galileo Galilei (1563–1642), who presented the study of the strength of solid bodies as one of the two "new sciences" in his *Discorsi*.[100] Galileo had tried to derive the ratio between the

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[100] Galileo Galilei, *Discorsi e dimonstrazioni mathematiche, intorno à due nuouve scienze attenti alla mecanica & i movimenti locali* (Leiden: Elsevier, 1638). For a translation of this work, see Galileo Galilei, *Dialogues Concerning Two New Sciences*, trans. Henry Crew and Alfonso de Salvio (New York: Dover Publications, 1954). For a discussion of Gailileo's work on the strength of materials, see Truesdell, *The Rational Mechanics* (n.15), 34–43; Timoshenko, *History of Strength of Materials* (n.15), 7–14; Benvenuto, *An Introduction* (n.15), 143–97.

absolute and the relative coherence of a body. In order to make the problem susceptible to a mathematical treatment, he had made some idealizations. For example, he presupposed that bodies were completely rigid and that breaking therefore occurred in one instant. On the basis of his idealized model, he was able to derive that the relative coherence of a body is half its absolute coherence.[101]

After Galileo, attempts were made to provide a more realistic mathematical treatment of relative coherence. Edme Mariotte (1620–1684) observed the discrepancy between Galileo's idealizations and the behavior of real wooden beams. Criticizing Galileo's assumption that the entire side of the beam broke simultaneously in one instance, Mariotte assumed that bodies like wood and iron were made of fibres that could be lengthened and that broke when the maximum amount of lengthening had been achieved.[102] On the basis of this model, Mariotte concluded that the relative coherence of a body is a third of its absolute coherence.[103]

G. W. Leibniz (1646–1716) provided another geometrical treatment of the problem, based on a different model. Van Musschenbroek provides a discussion of Leibniz's demonstration in his book.[104] Like Mariotte, Leibniz noted that Galileo's assumption was problematic and contrary to the observed behavior of breaking bodies.[105] Leibniz also conceived bodies as being made up of flexible fibres, but considered these fibres to be stretched like (musical) strings,

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[101] Van Musschenbroek, *Physicae experimentales* (n.13), 526. The demonstration provided by van Musschenbroek is more elaborate than that provided by Galileo, who "does not provide it, but presupposes it" according to van Musschenbroek (ibid., 527). See Galileo, *Dialogues* (n.101), 115–17.

[102] Benvenuto, *An Introduction* (n.15), 266. Benvenuto remarks that this also involves a conceptual change: Galileo saw fracture as a result of the maximum weight being exceeded, whereas Mariotte understood it as the maximal elongation being exceeded (ibid.). He further credits Mariotte with being the first to introduce elasticity into a discussion of relative coherence (ibid., 265).

[103] Benvenuto, *An Introduction* (n.15), 60.

[104] Ibid., 528–30.

[105] Gottfried Wilhelm Leibniz, "Demonstrationes novae de resistentia solidorum," *Acta Eruditorum*, July 1684, 321. Leibniz acknowledges Mariotte's work on the problem and refers to him as proposing that the relative coherence of a body is a fourth of its absolute coherence (On the fact that Leibniz takes Mariotte to propose a ratio of 1:4 instead of 1:3, see Truesdell, *The Rational Mechanics* [n.165], 61). Leibniz then says he "had the occasion of considering the problem in more depth, and examining it according to the laws (*leges*) of the geometers," which led him to find the true proportion and a proof that the relative coherence of a body is a third of its absolute coherence (Leibniz, ibid.).

at the same time resisting the pull exerted on them.[106] Leibniz further presupposed that the elongation of the fibre was proportional to the force exerted on them.[107] Tacitly assumed (but made explicit in van Musschenbroek's exposition) was that the force of resistance of the fibres is proportional to their elongation.[108] On the basis of this, Leibniz inferred that the relative coherence of a body is a third of its absolute coherence.[109] Van Musschenbroek's comment on Leibniz's treatment of the problem is the same as his comment on Galileo's treatment. The demonstration is considered as true but only provided that the elongation of the fibres of the body is indeed proportional to the applied force.[110] Observations and experiments, however, show this is not the case for all bodies. The variety of nature again trumps all attempts of capturing her in general rules:

> It follows from this that there is not one general rule given in nature expressing the same proportion between the respective and absolute coherence, which the geometers have tried to provide. Because the proportion has to be very different [in each case] due to the varying flexibility of bodies, which is truly shown by experience. If philosophers had first made several experiments with care, before working on this topic, they would have spared themselves much work, and they would have never devoted themselves to discovering one universal rule. Because there are almost as many different proportions between absolute and respective coherence to be found, as there are different bodies.[111]

This is confirmed by the results of van Musschenbroek's extensive series of experiments, in which the proportions range from 2:1 up to 18:1.

Despite his aforementioned mistrust of generalization, most emphasis in the literature is put on van Musschenbroek's experimental derivation of the inverse

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[106] Benvenuto describes Leibniz as treating "every fiber [. . .] [as] a spring connecting the beam to the wall" (Benvenuto, *An Introduction* (n.165), 269). This is somewhat imprecise, as Leibniz refers to an (elastic) string (*chorda*), not to a spring (Leibniz, "Demonstrationes novae" [n.105], 321).

[107] Leibniz says that this presupposition "has been confirmed elsewhere" but does not provide a reference for this (Leibniz, "Demonstrationes novae" [n.105], 322). For a discussion, see Truesdell, *The Rational Mechanics* (n.15), 61–62.

[108] Van Musschenbroek, *Physicae experimentales* (n.12), 529.

[109] For a discussion of Leibniz's demonstration, see Truesdell, *The Rational Mechanics* (n.15), 61–62; Benvenuto, *An Introduction* (n.15), 269–71.

[110] Van Musschenbroek, *Physicae experimentales* (n.12), 530.

[111] Ibid., 534.

proportionality between the strength of a beam and the square of its length.[112] What is not mentioned in the secondary literature, however, is that van Musschenbroek did not present these proportions as a *general* law or rule. At the end of the experiments from which he derived these proportions, he emphasizes that the derived proportions cannot yet be regarded as general rules:

> These are the first experiments in this learning about the strength of compressed bodies, which will hopefully be advanced further by others who examine the coherence of stones, bricks, metals, bones, and other bodies. Because that will be very useful for humankind. No universal rules can be established, nor proven to be universal, before innumerable experiments have been made. From our [experiments] we will derive some consequences, which are true for those [pieces of] wood. Whether they also hold for other bodies, I do not know.[113]

That van Musschenbroek was the first to rigorously pursue an experimental investigation of the strength of materials meant he had to design his own instruments and experimental set-ups. Truesdell notes that "to Musschenbroek is due the invention of special *testing machines* permitting systematic variations of experimental parameters in an easy succession of measurements."[114]

An example of this can be seen in the set-up used to measure a body's absolute coherence, which was based on the use of a Roman balance (AB in Fig. 2). The advantage of using a Roman balance was that the weight could be increased easily and in very small intervals by sliding the weight (C in Fig. 2) further and further. It also allowed the experimenter to instantly see the weight being applied.[115]

Already in the first series of experiments on absolute coherence reported by van Musschenbroek, the variety of nature shows itself. Before discussing his

[112] For example, Jozef Singer, Johann Arbocz, and Tanchum Weller, *Buckling Experiments, Basic Concepts, Columns, Beams and Plates* (New York: John Wiley & Sons, 1998), 181. Leonhard Euler (1707–1783) would later provide a theoretical derivation of a formula for the critical buckling load, which contained this inverse proportionality. For a discussion, see Truesdell, *The Rational* (n.15), 211–13. Euler does not mention van Musschenbroek's earlier experimental derivation of the proportionality (Truesdell, ibid., 213).

[113] Van Musschenbroek, *Physicae experimentales* (n.12), 658.

[114] Truesdell, *The Rational Mechanics* (n.15), 151.

[115] Van Musschenbroek added a small cord (SS in Fig. 2) that had the function of stopping the end of the balance when it fell, thus protecting the feet of the experimenter against injuries (van Musschenbroek, *Physicae experimentales* (n.12), 481).

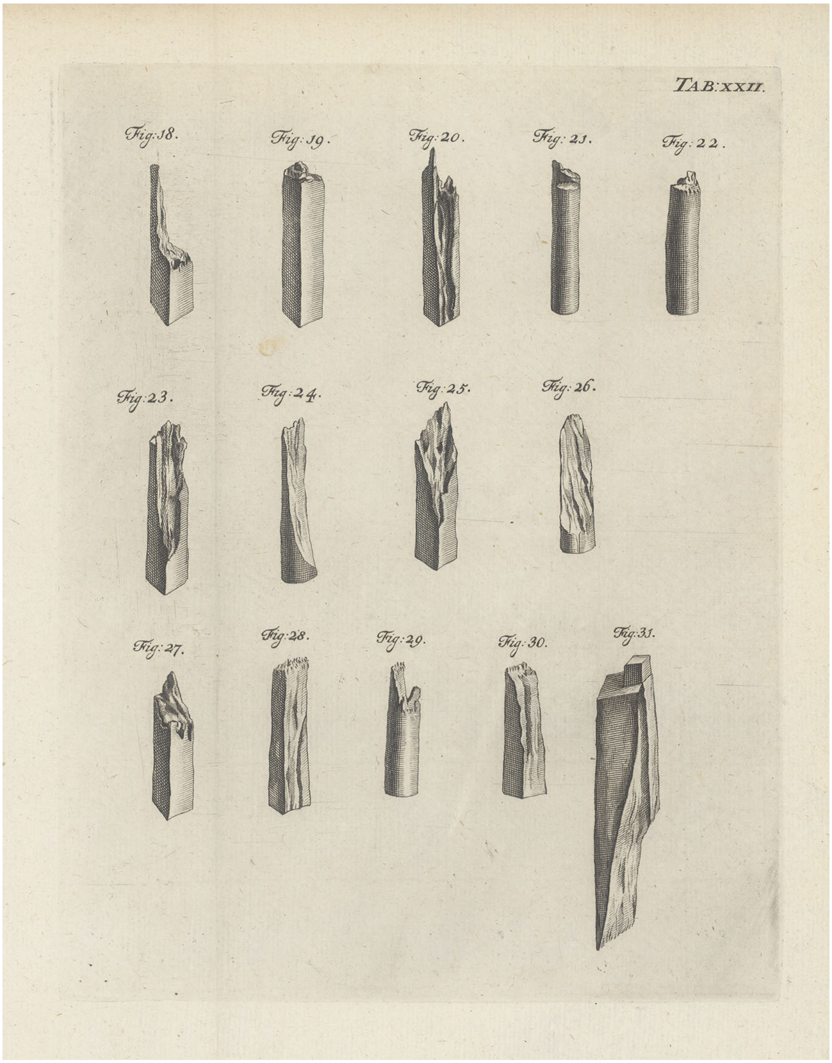

FIGURE 3. Selection of images of fractured pieces of wood (van Musschenbroek, *Physicae experimentales* [n.12], Tab. 22). Scan of copy of *Physicae experimentales* in the collection of Ghent University Library. Digital reproduction provided by Ghent University Library.

experiments on wood, van Musschenbroek says that “the results [of these experiments] are so wonderfully various, that every piece of wood has to be discussed separately.”[116] To underscore this variety, van Musschenbroek provides drawings of the shape of the specimens of wood after breaking. These

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[116] Ibid., 483.

pictures also have an informative function. Van Musschenbroek adds that knowing the way wood splinters might be useful knowledge for ship builders because soldiers on war ships are more often hurt by the splinters of wood than by cannonballs.[117]

Not only the way the wood fractured but also the weight that could be sustained by specific pieces of wood varied. Moreover, variations could be observed between different specimens of the same kind of wood. After providing his results for the experiments on wood, van Musschenbroek therefore adds the following disclaimer:

> These [experiments] have been performed carefully enough. However, I do not doubt that if they would be repeated, the outcome would be very different. Because a piece of wood will be more or less firm depending on whether the soil in which it grows is more or less watery, marshy, oily, salted. It will also cohere more or less depending on whether it has been planted in a warmer or colder region. Also, the wood will be more rigid or flexible, or stronger or weaker, depending on whether [the piece] that is used for the experiment, has been made from an older trunk or from a more delicate branch. Whether one chooses wood which has grown with very straight fibres, or with winding fibres, again a different coherence will be observed. It suffices to have brought this to mind once.[118]

Differences can even be seen with pieces of wood coming from the same type of tree, depending on whether the wood was taken closer to the center of the tree or closer to the bark.[119]

This kind of heterogeneity makes an idealized mathematical treatment of the cohesion of bodies problematic. Van Musschenbroek uses an example of different wires made from the same batch of copper. Experiments show that the strength of these wires was not the strength that would have been expected on mathematical grounds. He accounts for this in the following way:

> I believe this happens, because a metal is not as homogeneous, as it appears to the naked eye. Rather, it consists of parts which at places cohere more or less, because at some places more sulphur, salt, or mercury is deposited, which prevents the metal of having an equal strength.[120]

[117] Ibid., 483.

[118] Ibid., 494.

[119] Ibid., 484.

[120] Ibid. Up until the early modern period, metals were seen as composed of different substances. The idea that metals are composed of sulfur and mercury dates back to Arabic alchemy. Paracelsus (1493–1541) added salt to the list. For a short overview of the history of these

This does not mean however that nothing has been learnt from these experiments:

> From these experiments we learn that the coherence of copper does not accurately follow [its] thickness, so that if one would want a machine [made] from this metal, from which a given weight has to be hung, the metal has to be made thicker than what a calculation would indicate.[121]

For van Musschenbroek, the experiments reported in the *Physicae experimentales* are only the beginning, and much work remains to be done:

> These few tests are the true foundations of a science (*doctrina*) on the coherence of solid bodies. If only philosophers would explore the other bodies that are found on earth, using this or a similar method! Because without experiments this learning cannot make progress, for no mortal will determine *a priori*, how much the absolute or respective strength will be of a given body which has not yet been explored. [. . .] Therefore, people should be entreated to [. . .] perform experiments on bodies [and] leave behind the empty philosophy in which one only discusses causes and in which hypotheses are constructed [. . .] which fills the mind with vain learning, which is a waste of time, which empties [our] moneybags in a shameful way.[122]

True to these words, van Musschenbroek would continue to investigate the strength of bodies after the publication of his 1729 book. In the next subsection, I discuss further experiments performed by van Musschenbroek. These were ultimately published in the posthumous 1762 textbook.

3.2 The Research on Alloys

Van Musschenbroek not only treated the topic of the strength of materials in his 1729 *Physicae experimentales* but also included a chapter on the topic in the textbooks written for his students. In the final, posthumously published edition of this textbook, the chapter on cohesion is immensely expanded. Van Musschenbroek's main focus seemed to be on the strength of metals.

At the beginning of the section on the strength of metals, van Musschenbroek comments on their variety. Metals are delved up in different parts of the

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ideas, see William R. Newman, "Alchemical and Chymical Principles: Four Different Traditions," in *The Idea of Principles in Early Modern Thought*, ed. Peter R. Anstey (New York: Routledge, 2017), 77–97.

[121] Ibid.

[122] Van Musschenbroek, *Physicae experimentales* (n.12), 540.

world, and processed in different ways by metallurgists, "so that, although certain metals are called by the same name, they are not completely similar [or] regular, but [their] properties differ greatly."[123] This, he says, should be taken into account when looking at the results of his experiments:

> As long as metals are prepared that are similar to the ones that we used in our time, the experiments, that we have performed on [their] strength, will remain valid. But from the moment that they are melted, or prepared in another way, made ready in a more diligent or negligent way, or when they are mixed with other minerals, provided by nature in new mines, new experiments will have to be made.[124]

Van Musschenbroek also emphasizes the care he had taken to procure good metals, and to find out from which part of the world they had come. This extra care was not superfluous:

> Because generally those that are sold are wont to be mixed with several things, and the workers anxiously hide both what they mix in, and the way of doing this. After I had often observed and discovered that I had been fooled in this way, I have taken all precautions not to be deceived, so that I could provide accurate experiments and true results.[125]

In the 1729 publication, van Musschenbroek had only discussed experiments on metals.[126] Now, in line with the aforementioned emphasis on variety, he also provides results of tests made on different kinds of alloys. Van Musschenbroek thinks that the origin of the metal is an important variable to take into account. Experiments on alloys with Swedish copper, for example, are therefore not sufficient but should be supplemented by experiments on alloys made with copper coming from other regions. Van Musschenbroek mentions other sources of instability and uncertainty. One source of variability is that metals do not always fill the mold in which they are being casted equally well. The same metal can obtain cracks and internal holes in one kind of mold but be perfectly casted and thus stronger in another. Some metals are better casted in a heated mold, others in a lukewarm mold, others in a cold one.[127]

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[123] Van Musschenbroek, *Introductio* (n.64), 415.

[124] Ibid., 415.

[125] Ibid., 415.

[126] Van Musschenbroek, *Physicae experimentales* (n.12), 494–506.

[127] Van Musschenbroek, *Introductio* (n.64), 418.

After this preliminary discussion, van Musschenbroek presents the results of his research on different kinds of alloys.[128] He varies the ratio between the metals that go into the alloys. In some cases, the amount of one metal is held fixed, and the amount of the other metal is varied. An example of this can be found in the experiments on alloys of silver and Swedish red copper.[129] In other cases, the amount of each metal is held fixed in turn while the amount of the other is varied. An example of this can be found in the experiments on alloys of silver and red copper from Barbary. The latter experiment also provides examples of other recurrent features of the experimental reports. As in most (but not all) other reports, van Musschenbroek explicitly mentions the type of mold used, in this case a mold of sand from Brussels.[130] The experiment also provides an example of another variable that van Musschenbroek thought relevant, namely the origin of the metal being tested. Having tested alloys made from silver and Swedish red copper, he now tests alloys made from silver and red copper from the Barbary Coast.

At several points, van Musschenbroek refers to the customs of metalworkers.[131] He not only described these craft practices but also repeated artisanal operations, *and* he performed additional experiments. In this way, his research on the strength of materials exemplifies the three connotations that, according to Klein, "experimental history" had in Boyle's work.[132] However, Klein also points to the fact that in experimental history the absence of a theoretical framework was linked to "the additional absence of a methodological way of experimenting."[133] We have seen here how in his research practice van Musschenbroek also worked in a systematic way. In his research on alloys, he systematically varied the ratio between the metals forming the alloy. In line with the methodological remarks made in the oration on experimental method, he also made sure to vary the origin of the metals.

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[128] Ibid., 418–57.

[129] Ibid., 421.

[130] In an earlier paragraph, van Musschenbroek had left varying the mold as an exercise to the reader. He says that using different molds gives rise to differences in the strength and density of the metal (ibid., 421).

[131] At no point does van Musschenbroek provide names of individual craftsmen. For a more elaborate discussion of van Musschenbroek's interaction with craftsmen, see Present [Beck], *Learning in the World* (n.3), 128–130.

[132] Klein, "Experimental History" (n.17), 540.

[133] Ibid., 541.

4. HOW TO ASSESS VAN MUSSCHENBROEK'S RESEARCH ON THE STRENGTH OF MATERIALS

In the previous two sections, we have seen that both in theory and in practice van Musschenbroek emphasized the systematic variation of parameters in experimental research. Van Musschenbroek's emphasis on the necessity of varying experiments resonates with the recent work in the philosophy of experimentation by Friedrich Steinle. Steinle has introduced the concept of "exploratory experiments" to describe "a specific type of experimentation—an experimentation that is not, as in the "standard view," driven by specific theories."[134] Exploratory experimentation is typically undertaken in periods where "no well-formed theory or even no conceptual framework is available or regarded as reliable."[135] Although the notion of "exploration" might make one expect that exploratory experimentation encompasses a wide variety of experiments, Steinle emphasizes that his notion of exploratory experimentation is quite specific. That is, it is a type of experimentation characterized by a specific *epistemic goal*, namely "the goal of finding empirical rules and systems of those rules."[136]

Steinle's main aim is to argue that exploratory experimentation has its own systematicity, despite the fact that it is not theory-driven. He provides the following characterization of the procedures typical of exploratory experimentation:

> The most prominent characteristic of the experimental procedure is the systematic variation of experimental parameters. The first aim here is to find out which of the various parameters affect the effect in question, and which of them are essential. Closely connected, there is the central goal of formulating empirical regularities about these dependencies and correlations. Typically they have the form of "if–then" propositions, where both the if- and the then-clauses refer to the empirical level.[137]

As noted above, we have seen how van Musschenbroek emphasized the necessity of systematically varying experimental parameters in both theory and

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[134] Friedrich Steinle, "Entering New Fields: Exploratory Uses of Experimentation," *Philosophy of Science* 64 (1997): S65. A further discussion of this "standard view" is given in Friedrich Steinle, "Experiments in History and Philosophy of Science," *Perspectives on Science* 10, no. 4 (2002): 408–9.

[135] Steinle, "Entering New Fields" (n.134), S70.

[136] Ibid., S71.

[137] Steinle, "Experiments in History and Philosophy of Science" (n.134), 419.

practice. This systematic approach formed the main difference between van Musschenbroek's take on the construction of experimental histories and Klein's description of experimental history as being characterized by a lack of a methodological approach toward the experiments.

I have already mentioned how van Musschenbroek's explanation of cohesion in terms of an internal attractive force can be understood as following Newton's remarks on cohesion found in the *Opticks*. In Query 31, Newton asked, "Have not the small Particles of Bodies certain Powers, Virtues, or Forces, by which they act at a distance, not only upon the Rays of Light for reflecting, refracting, and inflecting them, but also upon one another for producing a great Part of the Phænomena of Nature?"[138] Newton referred to gravity, magnetism, and electricity as well-known examples of forces acting upon a distance. These examples, according to him, make it probable that "there may be more attractive powers than these."[139] He gave examples of chemical phenomena that could be explained in these terms, and also referred to the phenomenon of cohesion and the phenomenon of capillarity. He wrote that it was "the business of experimental philosophy to find them out."[140] Further in the Query, he explicitly frames this in terms of a search for laws.[141]

Van Musschenbroek's research as presented in the *Physicae experimentales* is clearly motivated by Newton's description of the "business of experimental philosophy." The phenomena investigated by van Musschenbroek are exactly those mentioned by Newton in the Query: magnetism, cohesion, and capillarity. Van Musschenbroek likewise construes this investigation as a search for laws and prioritizes this search for laws over the search for causes. His research, following his methodological views, took the form of a systematic variation of parameters. This resulted in the construction of an experimental history, which could then be used to discover regularities. Rather than being set apart, the construction of an experimental history thus formed part and parcel of experimental philosophy for van Musschenbroek.

Klein points to the connection between experimental history and a "pragmatic and utilitarian attitude toward experiments," which was not peculiar to Boerhaave but that was "entrenched at Leiden University."[142] We have likewise encountered examples of this in van Musschenbroek's

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[138] Newton, *Opticks* (n.93), 375.

[139] Ibid., 376.

[140] Ibid., 394.

[141] Ibid., 401.

[142] Klein, "Experimental history" (n.17), 535, 553.

experimental history on the strength of materials. Van Musschenbroek describes the differences between metals coming from different ores and provides his readers with details on the behavior of specific metals in the process of making alloys. At several places, van Musschenbroek comments on the utility of knowing the specific characteristics of these materials. In his report of the experiments on woods, he provides details on the way the wood fractured and includes drawings of individual fractured pieces of wood. According to him, this was useful knowledge for shipbuilders because sailors tended to get wounded from splinters of broken wood on ships.

The question of the precise and specific characteristics and behavior of different materials is a question central to the discipline of engineering. Nowadays, we would more readily associate the investigation of the strength of materials with engineering than with Newtonian natural philosophy. I would argue that van Musschenbroek's research on the strength of materials could be seen as part of the emergence of engineering as a discipline in the eighteenth century.[143]

In 1771, John Smeaton founded the Society of Civil Engineers, an event mentioned in the literature as a pivotal point in the emergence of the identity of the civil engineer.[144] In an article on Smeaton's work on the construction of the Eddystone lighthouse, Andrew Morris describes the experiments that Smeaton performed on the strength of hydraulic limes and shows how they also take the form of exploratory experimentation in Steinle's sense.[145] In 1755, Smeaton had traveled to the Dutch Republic. During these travels, he went to visit van Musschenbroek.[146] Van Musschenbroek's work on the strength of materials was also taken up by other late eighteenth-century figures working on topics related to civil engineering. Charles Augustin Coulomb (1736–1806), for example, used van Musschenbroek's results in his own work.[147]

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143. For a recent overview of the literature on this topic, see Hélène Vérin and Irina Gouzévitch, "The Rise of the Engineering Profession in Eighteenth Century Europe: An Introductory Overview," *Engineering Studies* 3, no. 3 (2011): 153–69.

144. Ibid., 161.

145. Andrew M. A. Morris, "English Engineer John Smeaton's Experimental Method(s): Optimisation, Hypothesis Testing and Exploratory Experimentation," *Studies in History and Philosophy of Science*, no. 89 (2021): 283–94.

146. Andrew M. A. Morris, "'The Joint Labours of Ingenious Men': John Smeaton's Royal Society Network and the Eddystone Lighthouse," *Centaurus* 63, no. 3 (2021): 513–31, on 518.

147. For an overview of the material of van Musschenbroek used by Coulomb, see Jacques Heyman, *Coulomb's Memoir on Statics: An Essay in the History of Civil Engineering* (London: Imperial College Press, 1997), 80–81. For an assessment of Coulomb in relation to the development of eighteenth-century engineering, see C. Stewart. Gilmor, *Coulomb and the Evolution of*

This reference to two important figures in the history of eighteenth-century engineering is of course a far cry from an elaborate analysis of the place of van Musschenbroek's work in the emergence of engineering as a discipline. Such an analysis cannot be provided here. However, the fact that this process took place during this period and that his results were used by engineers allows us to assess van Musschenbroek's experimental history on the strength of materials in another way.

We have seen how van Musschenbroek himself presented (experimental) histories as a necessary first step in experimental philosophy. One needed to produce extended (experimental) histories before one is able to find laws and (eventually) causes. We have seen how van Musschenbroek himself presented his research into the strength of materials in this way and how this research could be seen as motivated by the suggestions made by Newton in the *Queries* of the *Opticks*. Seen in this light, van Musschenbroek's project was not very successful. He did not succeed in formulating laws analogous to the law of universal gravitation. Except for the law regarding buckling, no general regularities appear to be found in the plethora of experimental results published by van Musschenbroek.

We have compared van Musschenbroek's take on the construction of (experimental) histories and their role in the search for regularities with Steinle's take on exploratory experimentation. In both cases, experiments are a means to an end, namely to find empirical regularities. Approaching van Musschenbroek's research in light of the emergence of engineering as a discipline, however, invites us to assess van Musschenbroek's results in another way. Rather than being a means to an end, the experimental results are an end in itself. From an engineering perspective, knowing the characteristics of very specific materials is of utmost importance. Van Musschenbroek's experimental history then becomes a valuable source material for anyone interested in using materials for constructions.

CONCLUSION

I started this article with a summary of van Musschenbroek's methodological views. These were characterized by a tension between generality and specificity. The variety and complexity of nature led van Musschenbroek to point at

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Physics and Engineering in Eighteenth-Century France (Princeton, NJ: Princeton University Press, 2017). Coulomb's relation to van Musschenbroek's work is likewise discussed (ibid., *passim*).

the limits of our knowledge and the necessity of taking the variability of nature into account.

Although he considered mathematics to be a powerful tool in physics, he also emphasized that we should stay conscious of its limits and remain within those limits in order not to abuse mathematics. More precisely, we should remain conscious of the fact that in mathematics we reason with abstract ideas that do not completely represent all the properties that bodies have in the external world.

This emphasis on the specificity of different kinds of bodies, found by means of experimental research, reoccurred in van Musschenbroek's thinking on laws of nature. Throughout his career, van Musschenbroek increasingly came to emphasize the variety of nature, leading him to become sceptical of general laws.

The complexity of nature also played an important role in van Musschenbroek's thinking on the method of performing experimental research. It also further clarified his moderately skeptical stance toward the search for causes: so many variables are at play that a lot of experimental research must be done to find a link between a determinate cause and an effect. Van Musschenbroek heavily emphasized the need to repeat and vary one's experiment in order to identify as many relevant variables as possible and to remove hidden sources of disturbances.

In his discussion of these topics, van Musschenbroek repeatedly presented the construction of (experimental) histories as a fundamental first step in experimental philosophy. Only after a history was constructed should one look for laws and causes.

All these points recurred in van Musschenbroek's research on the strength of materials. In the *Physicae experimentales* of 1729, he described the aim of this research as a search for laws. The results published in the work can then be seen as an experimental history, constructed as a first step in the process of finding these laws. In the same work, van Musschenbroek discussed earlier treatments of the strength of materials found in the work of Galileo, Mariotte, and Leibniz. In line with the aforementioned views on the limitations of mathematics, he pointed at the limitations of their abstract and purely mathematical treatment of the topic. Based on his experimental research, he formulated a law regarding the phenomenon of buckling, but in line with his views on laws of nature emphasized that this regularity should be seen as valid only for pieces of wood, as wood was the only substance he experimented on. In general, van Musschenbroek's experimental practice in the research on the strength of materials was consistent with his views on experimental method. The research consisted in an elaborate and systematic series of experiments in which specific parameters were varied. In the research on alloys, performed later in his career, these parameters included the ratio between the metals in the alloy, the origin of the metals, the type of mould used, and the temperature of the mold. The selection of these parameters and his description of the process of casting illustrated his acquaintance with existing metallurgical practices.

Van Musschenbroek's research on the strength of materials could be seen as building on the suggestions that Newton provided in the *Queries* in his *Opticks* and thus as a project in Newtonian experimental philosophy. Van Musschenbroek was looking for the laws related to the phenomenon of cohesion, a form of attraction analogous to gravity. In line with his own methodological views, the construction of an experimental history formed the necessary first step in the search for those laws.

Van Musschenbroek failed to find laws analogous to the law of universal gravitation. From Klein's discussion of Boerhaave's experimental history, we have, however, learned that experimental history was informed by a utilitarian attitude. We encountered several examples where van Musschenbroek pointed at the utility of his experimental results, such as the behavior of different kinds of wood when breaking, or the specific practical properties of different types of alloys. Van Musschenbroek's descriptions of the practices of metalworkers and the repetition and extension of these practices in his own experimental research also align with Klein's description of experimental research. The biggest difference between Klein's take on experimental history and van Musschenbroek's theory and practice of constructing experimental histories was that in the latter case the experimental research was characterized by a method that aligned with Steinle's concept of exploratory experimentation.

In my final section, I have suggested that reading van Musschenbroek's history on the strength of materials in light of the emergence of engineering as a discipline in the eighteenth century provides a more positive picture of van Musschenbroek's results. Although it didn't provide a basis on which to establish laws, his work did provide a foundation for further engineers to work on and provided practitioners with information on the properties of specific materials. However, the specific place that van Musschenbroek's work takes in the emergence of engineering as a discipline and the way his results were used by practitioners are topics that await further research.

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