Introduction*

Objects of Understanding – Historical Perspectives on Material Artefacts and Practices in Science Education

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The history of science education remains an underexplored and underrepresented topic within the history of science, despite the crucial role that science education plays in the formation, stabilisation, dissemination, movement and transformation of scientific knowledge and scientific practises. This is true even more so for the material cultures and practices of science teaching. A broad variety of material practices that were labelled as demonstrations or experiments by teachers and students, model making, object handling, dissection, image projection and showcasing objects have been central to science education throughout its history. Extensive teaching collections, teaching infrastructure, and the built environment at schools, colleges and universities bear witness to the importance of these cultures and practices, which largely remain unstudied by historians of science (Wittje, 2023).

Some 13 years ago, we were writing the introduction to *Learning by Doing: Experiments and Instruments in the History of Science Teaching* (Heering & Wittje, 2011). In some respects, this current edited volume can be seen as a continuation, yet also an expansion of *Learning by Doing*. Together with the authors of this volume, we no longer only look at instruments and demonstrations, but also address other material objects, collections and practices that have been used in educational processes. The last couple of decades have witnessed a rapidly growing interest in university collections es-

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pecially in Europe, most of them related to teaching, which aim to preserve the rich material heritage of universities (Soubiran et al., 2009). Studies of school collections, in contrast, remain sporadic.[1] A substantial number of these studies address teaching collections, but not the teaching with the objects that form the collection (Bernard, 2018; Canard et al., 2022; Malpeli, 2021). However, some works have appeared in recent years that deal with the history of instruments and experiments within the practice of science education (Bertozzi, 2021; Heering, 2023; Markert, 2022; Markert, 2024; Vaupel & Preiß, 2022).

While we have to conclude that the research field of the history of material cultures of science education has not changed much since 2011, this volume once again brings together histories and case studies from the 18th century to our contemporary times, which, taken together, demonstrate the potential of the field. The studies have become more global: In addition to a series of case studies based in Europe or North America, Roland Wittje investigates the attempt to implement German methods of physics education in India at IIT Madras, and Maria Gabriela Mayoni discusses the establishment of objects, collections and practices for teaching natural history in Argentina. Panagiotis Lazos presents a case in which a scholar from the Greek periphery develops a teaching device that made it into the European centres. Together, these studies address how teaching objects, collections and practices travel, what might obstruct their travel, and how they are shaped and transformed within a local environment and social context. As Mayoni concludes, 'local and foreign materials coexisted. …. A dialogue between a type of 'universal science' … with local nature … was formed in the classroom'.

Infrastructures and built environments are a recurring topic in several papers. Jamilla Notebaard and Dulce da Rocha Gonçalves discuss the use of magic lanterns as omnipresent teaching devices in the early 20th century Netherlands. In doing so, they highlight the creation of the respective architecture and infrastructure, such as J.W. Moll's lecture hall in Groningen, which was designed in a special manner that made it particularly suitable for lantern projections. Environmental aspects play a key role in Wittje's contribution as well – here however in a significantly different manner: Wittje demonstrates how the climate and architectural environment in Madras presented a challenge for the transfer of the Robert Pohl's system of lecture demonstrations established in Göttingen. The built environment of teaching devices is also a main concern of Jean Davoigneau, Delphine Issenmann and Loïc Jeanson, who discuss the integration of both research and teaching at the Strasbourg observatory, which distinguished it from other French and German observatories. Together, these studies demonstrate that teaching instruments, collections and practices need to be studied within their built environments, environmental conditions, and within scientific infrastructures.

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1 See Rivera Colomer, 2024; Simon et al., 2009; and Talas, 2010 and 2012 as examples for studies of scientific instrument collections in schools.

Three contributions come from the early 18th century and address, as Sofia Talas put it, the 'beginnings of experimental physics teaching'. Talas discusses Giovanni Poleni and his attempts to establish an experimental program at the University of Padova. One of the references for Poleni was the teaching in Leiden – Leiden as a reference place for early experimental physics teaching reappears in the contributions by Jip van Besouw and Peter Beck on the one hand, and Peter Heering on the other. The former focus in their study of teaching hydrostatics in particular on the relation between mathematical demonstrations and the teaching with instruments. The latter addresses 's Gravesande's practice with the hydrostatic balance; in doing so, he particularly discusses performative aspects of the practice with the instrument.

Van Besouw and Beck, Heering, and Davoigneau et al. all deal with the relationship between teaching and research instruments, though in different ways. Van Besouw and Beck argue that van Musschenbroek's and 's Gravesande's fountains cannot be reduced to pedagogical devices to teach students with little or no mathematical skills, as these were important instruments in the investigation of fluid flow. Heering studies the differences in 's Gravesande's hydrostatic balance in its modification as a demonstration instrument, and Davoigneau et al. discuss the transformation of a meridian circle from a research instrument into a teaching device.

Whilst these three papers address the work of academics at universities, other papers discuss school teaching and individuals who are less known to historians of science. Rosanna Evans presents her research on school practitioners developing and building their own teaching devices. In doing so, she shows which strategies teachers employed to enable themselves to enrich their classes by tailoring apparatuses to their teaching. Stephen Johnston introduces the schoolteacher Thomas E. Dexter, "not a well-known figure in the history of either science or education". Dexter developed and marketed the Portable Museum, which were educational boxes to teach object lessons to children in both formal and non-formal settings.

An important aspect discussed in Johnston's paper is the marketplace for teaching objects and collections, which is a recurring topic in several papers. While Dexter's Portable Museum introduced raw materials and trade products from different parts of the empire, it was itself a trade product, manufactured and sold over an extended period. Jörg Zaun and Kirsten Vincenz discuss the object tableau as a different type of educational box, which displays raw materials or finished products. Most case studies address objects that required or at least enabled a manipulative interaction either between the learner or with the teacher and the object. This is not the case with the kind of educational boxes that Zaun and Vincenz introduce: in the object tableau, the objects are not meant to be removed but to be studied in their didactic arrangement through the covering glass. In a naïve perspective, one may argue that these object tableaus speak for themselves, yet, as Zaun and Vincent demonstrate, this is not the case.

In an ethnographic approach, Jochen Lange describes the processes involved in the current design of teaching instruments at a major company in the field. In doing so, he approaches the process of developing new teaching objects as materials that facilitate science learning, and as commercial products. Richard Kremer discusses how electronics was introduced in science teaching, highlighting the importance of experimental kits for teenagers to build their own electronic devices, and modular boxes to demonstrate radio circuits sold by the instrument company Leybold. With Kristen Halverson's paper, the marketplace moves away from school science and undergraduate science teaching, to instructing practicing medical professionals. In her study of the promotion of certain medical instruments in Swedish and Danish medical journals, Halverson shows that in order to establish certain instruments as standard devices, educating professionals remotely through journal articles had to be done differently in both countries.

David Munns takes us to teaching reactors at American Universities during the Cold War. Just as these reactors were needed to train a growing number of nuclear engineers, they needed to navigate the politics of atomic energy and nuclear safety, and the expectations and promises of the Atomic Age. Along with Johnson's and Wittje's contributions, Munns' paper highlights the political, social and cultural context of the materiality of science education in which it operates, and from which it cannot separate.

While this edited volume is not a coherent presentation, nor an exhaustive or even conclusive treatment of material cultures of science education, the different chapter clearly illustrate why historians of science need to engage with the topic. If historians of science have dealt with the history of science education at all, they mainly focused on the role of science education for the formation and reproduction of scientific communities (Mody & Kaiser, 2007). However, we have to acknowledge that most science teaching has taken place outside of academic institutions. It appears to be a necessity that we do not speak of science education in general terms, but that we analyze it in a more differentiated way: At one end of the scale is the non-formal education of young people and general school education, both of which arise from socio-political concepts and have a function in the creation of useful members of society. At the other end is the qualification of scientific researchers who are to become members of the relevant collective and thus receive a very specific introduction to the subject in question and the culture established in it (perhaps only locally). In between are, for example, technical training courses that qualify students for certain professions outside of research, but also degree courses that aim to qualify students for a corresponding profession (such as practicing doctors or pharmacists).

The relationship between science and the public has become a major theme within history of science in recent decades. Somehow, formal science education in schools, colleges and technical training has, by and large, not been part of this endeavour, which is surprising give the crucial role that formal education plays in the coproduction of science and society. We need to add, of course, that a number of historians of science have written about the relationship between formal science education in schools and the formation of society (see, for example, Roberts, 2012; Kohlsted, 2010; Nyhart, 2009; Olesko, 1989).

When discussing educational processes in the natural science disciplines, it seems necessary to consider the differentiation called for above. How did the reproduction of researchers in the natural sciences take place? What demands have been placed on scientific training by practitioners (including at university level), by whom and with what demands? And finally, how was science education conceived in the context of a general education, what role was ascribed to it and what demands were associated with it? The question is not only what was taught, but also what was learned. And here it is less important to ask what content was learned, but rather what understanding of nature, of science and of one's own role in the world was achieved through the respective educational processes. We have to address these and other questions as historians of science if we claim to take science educations seriously. For this, we need to study not only science textbooks, but also teaching devices and teaching collections, which became central to the practice and epistemology of science and its pedagogy in the early 18th century, and remained so until this day.

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At the Beginnings of Experimental Physics Teaching

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Introduction

The experimental natural philosophy that emerged in the course of the seventeenth century was mainly practiced within academies and learned societies, where observations and experiments about various aspects of the natural world were regularly carried out, attended by the academies' members. Only in a few universities, some lectures illustrated by demonstrations were proposed at the end of the century, like for instance in Paris or Leyden. At the University of Paris, Pierre Polinière actually held a series of lectures based on experiments within a philosophy course, describing his demonstrations in the book *Experiences de Physique* (Polinière, 1709). In Leyden, Burchard de Volder introduced experiments in his natural philosophy lectures from 1675 – a *Theatrum Physicum* was purposely built to host these new lectures at the end of 1675 (de Clercq, 1997; Strazzoni, 2019; Wiesenfeldt, 2002). De Volder was mainly interested in pneumatical and hydrostatical experiments, and so was Wolferd Senguerd, who started teaching natural philosophy in Leyden a few years later. Senguerd was allowed to hold his lectures in the *Theatrum Physicum* from 1705, but he found the instruments left by de Volder neglected and damaged (Wiesenfeldt, 2002; Molhuysen, 1913–1924).[1] There was actually no continuity in the use of instruments in teaching at the time: experiment-based lectures were isolated cases.

However, the situation was about to change very rapidly in a few years: from the early eighteenth century, new experimental lectures, which were to be called "experimental philosophy" or "experimental physics" lectures, started spreading from Eng-

1 My warmest thanks to Steffen Ducheyne for sharing with me his manuscript chapter on Hermann Boerhaave, which provided me with many valuable details about de Volder and Senguerd.

land throughout Europe. Their diffusion was rapid and can be seen as a "flood of Anglo-Dutch Newtonianism", as John Heilbron called it (Heilbron, 1979, p. 141). John Keill and William Whiston, both Newton's pupils, introduced these new lectures in Cambridge and Oxford universities, and the new lectures were also offered in London to a wide public. The connection with the Royal Society, chaired by Newton from 1703, was tight. The lectures widely drew on what had been performed during previous meetings of the Royal Society, and most of the lecturers were or became Fellows of the Royal Society (Morton & Wess, 1993), like for instance John Theophilus Desaguliers, who contributed significantly to the success of the new lecture-demonstrations (Soares, 2016). Desaguliers, after replacing Keill at the University of Oxford, moved to London, where he gave public experimental philosophy lectures from 1713. He travelled a lot in England and abroad, and presented his lectures in his book *A course of experimental philosophy.* Translated into many different languages, this treatise remained very popular during the whole eighteenth century (Desaguliers, 1734–44).

Two Dutchmen, Willem Jacob 's Gravesande and Pieter van Musschenbroek, both strenuous supporters of Newtonianism, then played a central role in spreading the new experimental philosophy lectures on the Continent (de Clercq, 1997). They gave lecture-demonstrations at the universities of Leyden and Utrecht, going beyond the English models they had experienced in London: they not only widened the topics covered, but also introduced new experiments and teaching devices. The treatises they published about their courses enjoyed a huge success and were translated into various languages ('s Gravesande, 1720–21, 1725, 1742; Musschenbroek, 1734, 1739, 1751, 1762). Their lectures attracted students from all over Europe, such as Jean-Antoine Nollet, known as *l'Abbé Nollet*, who was to become one of the main supporters of the new way of teaching (Heilbron, 1975). Nollet's textbooks also became very popular (Nollet, 1738, 1743–1764, 1770).

The lively activities carried out by Nollet and the Dutch and English experimental philosophy pioneers brought forth striking results: the new lecture-demonstrations reached the whole Europe and the British colonies in North America within a few decades. Chairs of experimental philosophy were created in many universities and cabinets of physics, homogeneous collections of scientific instruments, were set up mainly for teaching purposes though some instruments, like electrostatic generators for instance, were also used for research activities.

Though Newtonian lecture-demonstrations certainly dominated the scene, other lecturers, not related to the Anglo-Dutch stream, also included experiments in their teaching in those years. In Germany, in particular, the experimental lectures given in Altdorf by Johann Christoph Sturm at his *Collegium Curiosum* from 1672 (Sturm, 1676) influenced several university professors, like Christian Wolff, who taught in Halle from 1706 and in Marburg from 1723. Wolff's Cartesian experimental way of teaching spread to several universities: it arrived in Kiel, in Leipzig and in Uppsala (Heilbron, 1979). Nonetheless, it should be noted that Wolff's successors also included in their lectures elements of the Anglo-Dutch experimental lectures. The various models of lecture-demonstrations introduced in those years actually merged quite quickly, and the case of the University of Padua is paradigmatic in this sense. The chair of experimental philosophy, created there in 1738, was assigned in February 1739 to Giovanni Poleni, who was regarded as an expert of experimental natural philosophy (Talas, 2013; Del Negro, 2013; Salandin & Talas, 2000; Grandjean de Fouchy, 1763).[2] To set up his new lectures, Poleni followed the Anglo-Dutch pattern: he proposed many experiments designed by Desaguliers, 's Gravesande and Musschenbroek, and he entitled the manuscript notes of his lectures *Physices elementa mathematica experimentis confirmata,* just like 's Gravesande's well-known treatise. Furthermore, in his letters, Poleni often enthusiastically mentioned "Musschenbroek, so well-known in the art of experimenting",[3] or the "skilfull experimental philosophers, P. Musschenbroek and Guglielmo Giacomo 's Gravesande".[4] However, Poleni also mentions "Christian Wolff in Germany", together with "Desaguliers in England and in Holland Musschenbroeck and s' Gravesand" who all, according to him, "perform experiments as an Art".[5] An instrument acquired by Poleni to study the refraction index of liquids is particularly relevant to show how the Newtonian and Wolffian experimental teaching merged (Fig. 1), designed by Wolff,

Fig. 1 Instrument to study the refraction index of liquids. Designed by Christian Wolff, it was made for Giovanni Poleni by Philippe Vayringe in the early 1740s. The liquid to be studied was put in the prism container (on the right in the photograph). The light entering through the lateral hole was deviated as it passed through the liquid, and the mobile arm was then moved until the refracted ray of light hit the square wooden piece at the extremity of the arm. Giovanni Poleni Museum, University of Padua.

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2 Poleni taught at the University of Padua from 1710, holding at first the chair of "Astronomy and Meteors". He then started teaching natural philosophy in 1715 and was assigned the chair of mathematics in 1719.

3 "Il Musschenbroek, si celebre nell'arte di esperimentare". Poleni, G., letter to Zendrini, 12 febbraio 1739: BMVe, Cod. It. IV, 643 (=5504), c. 19–20.

4 "valentissimi filosofi sperimentali, P. Musschenbroek e Guglielmo Giacomo 's Gravesande". Poleni, G., letter to the Venetian *Riformatori*, may 1761: BMVe, Cod. It., X, 313, c. 78.

5 "li signori Cristiano Wolfio in Germania, Desaguiliers in Inghilterra et in Ollanda Mussembroeck e s'Gravesand. Questi degli esperimenti fanno un'arte". Poleni, G., letter to Morosini, s. d.: BMVe, Cod. It., IV, 592 (= 5555), c. 191.

the device was made by Philippe Vayringe, an instrument-maker and lecture-demonstrator at the Court of Lorraine, who had spent time in England to learn from Desaguliers about the new teaching experiments and instruments (Talas, 2012 and 2013).

In the last decades, some studies have examined eighteenth-century lecture-demonstrations and cabinets of physics (de Clercq, 1997; Morton & Wess, 1993; Bennett & Talas, 2013), but many aspects still need to be further analyzed, such as the processes of diffusion of the new lectures, their shared features and local peculiarities, and the national and international networks that linked scientists to one another. A complete and detailed analysis on a European scale goes beyond the scope of this paper. The present work is based on the study of the first main experimental philosophy treatises and cabinets, as well as on letters and manuscripts related to Giovanni Poleni, who can be regarded as a paradigmatic first-generation lecture-demonstrator. After examining the main features of the new lecture-demonstrations, the paper will discuss their audiences and focus on the challenges the first professors of experimental philosophy had to face, such as finding a balance between mathematics and experiments, setting up structured and meaningful courses, and developing teaching methodologies that took into account students' needs. We will also see the specific skills professors were expected to have, as they were supposed to design new experiments and instruments and to know how to choose, use, handle, preserve and repair scientific instruments. The paper will finally examine the impact of 18th-century experimental philosophy lectures, underlining how they contributed to the birth of physics in a modern sense and to shaping physics teaching up to the 19th and 20th century. We will also see how the new lectures strongly enhanced science popularization and contributed to bring forth new generations of physicists from the early 19th century.

Main features and audience of the new lectures: science becomes public

One of the aims of the new experimental philosophy lectures was to provide direct and immediate demonstrations of Newton's philosophy, as 's Gravesande wrote to Newton in 1718:

> I begin to hope that the way of philosophizing that one finds in this book [Newton's *Opticks*] will be more and more followed in this country, at least I flatter myself that I have had some success in giving a taste of your philosophy in this university. As I talk to people who have made very little progress in mathematics I have been obliged to have several machines constructed to convey the force of propositions whose demonstrations they had not understood. By experiment I give a direct proof of the nature of compounded motions, oblique collisions, and the effect of oblique forces and the principal propositions respecting central forces (de Clercq, 1997, p. 76).