The Laboratory Challenge

Some Revisions of the Standard View of Early Modern Experimentation

*By Ursula Klein**

ABSTRACT

An examination of the use of the word "laboratory" before the nineteenth century yields two striking results. First, "laboratory" referred almost exclusively to a room or house where chemical operations such as distillation, combustion, and dissolution were performed. Second, a "laboratory" was not exclusively a scientific institution but also an artisanal workplace. Drawing on the historical actors' use of "laboratory," the essay first presents (some necessarily scattered) evidence for the actual correspondence between artisanal and scientific laboratories in the eighteenth century. A particularly instructive case is the way the equipment of the laboratory of the Prussian Academy of Sciences was acquired. There was, in this case, a direct transfer of instruments, vessels, and materials from a pharmaceutical to an academic laboratory. The essay then argues that we ought to distinguish between two different experimental traditions in the early modern period: experimental philosophy and the laboratory tradition that meshed studies of nature with technological innovation.

IN THE LATE 1790S, the German poet Novalis (Friedrich von Hardenberg) proclaimed that "every place must have its naturalists [*Naturforscher*] and laboratories." Like his Romantic colleague and friend Friedrich Schlegel, who observed that poetry and writing are "permanent experimentation," Novalis understood laboratories as the most exquisite manifestation of human creativity.[1] At the time laboratories were indeed ubiquitous in Europe, although they did not exist in all experimental disciplines. Nor were they unequivocally sites of learned inquiry into nature or "scientific" experimentation. What Novalis and Schlegel had in mind when they celebrated laboratories was not the seemingly open-ended knowledge-producing machinery of modern research laboratories, which—if indeed such pure research laboratories ever existed at all—certainly did not exist in their day.

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[1] Paul Kluckhohn and Richard Samuel, eds., *Novalis Schriften: Die Werke Friedrich von Hardenbergs* (Darmstadt: Wissenschaftliche Buchgesellschaft, 1968), Vol. 3: *Das Philosophische Werk II*, p. 179; and Ernst Behler, ed., *Kritische Friedrich-Schlegel-Ausgabe* (Munich: Schöningh, 1967), Vol. 18, Sect. 2, p. 215.

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"Laboratories," or "elaboratories," began to proliferate in the course of the sixteenth century, and at that time they were exclusively sites of alchemy. At the courts of the German-speaking countries, in particular, alchemical laboratories became a fashion.[2] In the courtly laboratories, but also in some laboratories established at monasteries, alchemists, *Laboranten*, and some other practitioners distilled medicines, analyzed ores and salts, and performed endless trials to transmute base metals into gold. In the century to follow, chemical laboratories spread to universities (such as those of Leiden, Marburg, and Altdorf), botanical gardens (such as the Jardin Royal des Plantes in Paris), the Académie Royale des Sciences in Paris, and other academic institutions such as the Ashmolean Museum at Oxford. At the same time, "laboratories" were also established at apothecaries' shops and in the mining industry (e.g., the Laboratorium Chymicum of the Swedish Board of Mines, founded in 1683); by the end of the seventeenth century the pharmaceutical trade had become the most important supporter of laboratories. Laboratories continued their triumph in the eighteenth century, when they were institutionalized at many European universities and academies as well as in the newly founded professional and technical schools. The term "laboratory" was by then also more frequently used—instead of "shop," "workshop," "*Werkstätte*," "*Arbeitsstätte*," "*atelier*," "*boutique*," or "*bodega*"—to designate innovative sites of material production that employed techniques of smelting, combustion, distillation, dissolution, precipitation, and other "chemical" operations. In the eighteenth century we encounter artisanal "laboratories" in apothecaries' shops, foundries, assaying shops, mints, arsenals and gunneries, dyeing manufactories, porcelain manufactories, chemical factories, distilleries, and perfumeries. The preparation of chemical remedies, the making of gunpowder, the chemical analysis of ores and useful salts, the quality control of dyestuffs, the improvement of porcelain manufacture, the production of mineral acids, the distillation of spirits of wine and liqueurs, the preparation of perfumes and pomades—all of these kinds of commercial production, as well as the planning and control of production, often took place in "laboratories."

In the eighteenth century the word "laboratory" turned up in many different types of texts, ranging from medical edicts, letters of state officials, governmental regulations, and applications for privileges, to treatises on metallurgy, pharmacy, and fireworks, to experimental reports and chemical textbooks, and all the way to dictionaries and encyclopedias. A close examination of the use and meaning of this word before the nineteenth century thus yields two striking results. First, "laboratory" referred almost exclusively to a room or house where chemical operations such as distillation, combustion, smelting, dissolution, and precipitation were performed.[3] Unlike chemistry, the other evolving experimental disciplines of the early modern

[2] See Pamela H. Smith, "Laboratories," in *The Cambridge History of Science*, Vol. 3: *Early Modern Science*, ed. Katharine Park and Lorraine Daston (Cambridge: Cambridge Univ. Press, 2006), pp. 290–305; and Tara E. Nummedal, "Practical Alchemy and Commercial Exchange in the Holy Roman Empire," in *Merchants and Marvels: Commerce, Science, and Art in Early Modern Europe*, ed. Smith and Paula Findlen (New York: Routledge, 2002), pp. 201–222. Here and in what follows I give only a few examples of the relevant primary and secondary sources. For a more complete bibliography see Ursula Klein, "Apothecary Shops, Laboratories, and Chemical Manufacture in Eighteenth-Century Germany," in *The Mindful Hand: Inquiry and Invention from the Late Renaissance to Early Industrialisation*, ed. Lissa Roberts, Simon Schaffer, and Peter Dear (Amsterdam: Koninklijke Nederlandse Akademie van Wetenschappen, 2007), pp. 247–276; and Klein, "Die technowissenschaftlichen Laboratorien der Frühen Neuzeit," *NTM*, 2008, *16*:5–38.

[3] A notable exception is the Laboratorium Mechanicum of the Swedish Board of Mines, established in Falun in 1700 as a supplement to the earlier Laboratorium Chymicum. See Svante Lindqvist, *Technology on Trial: The Introduction of Steam Power Technology into Sweden, 1715–1736* (Uppsala: Almqvist & Wiksell, 1984), p. 67.

period did not establish "laboratories."[4] Second, the early modern laboratory was by no means exclusively a *scientific* institution. Well into the nineteenth century the word "laboratory" was also used for artisanal, or proto-industrial, chemical workplaces.[5]

This use of the word "laboratory" corresponds with the fact that the Latin word "*laborare*," from which "laboratory" is derived, meant any kind of manual work, including commercial labor. Accordingly, Diderot and d'Alembert's *Encyclopédie* translates "laboratory" ("*laboratoire*") with "shop" ("*boutique*") and defines it as a "closed and covered place" that "contains chemical equipment [*utensils*]" such as furnaces, vessels, and instruments; Johann Heinrich Zedler's *Universal Lexicon* translates "laboratory" with "labor- or workhouse" ("*Arbeits- oder Werkhaus*")—a place where "chemical work" ("*chemische Arbeiten*") is done—and highlights "the place in the artillery where gunpowder and other materials pertaining to firework" are prepared. Similarly, the economic-technical encyclopedia compiled by the German cameralist Johann Georg Krünitz explains that a "laboratory" is a "labor- or workhouse" ("*Arbeits- oder Werkhaus*") and that the term is mostly used to designate "the place in chemistry and in pharmacy that is suited for chemical work" and "the house in which gunsmiths and sergeant-artificers manufacture their materials."[6]

What shall we make of this linguistic peculiarity, which is at odds with our present understanding of "laboratories" as places of scientific teaching and research, academic or industrial, and as the privileged and elite sites of experimentation in many different disciplines? Was the older usage mere rhetoric that had no, or little, bearing on what laboratories were in reality? Or is it possible to flesh out this early terminology with local stories and historical analyses? I argue in this essay for the latter alternative. There are good historical reasons why chemists needed laboratories; and there was also a strong correspondence between artisanal and academic laboratories in the early modern period, including the eighteenth century. In what follows, I will first explain these two arguments and then discuss some consequences for our understanding of the emergence and development of the experimental sciences.

LABORATORIES AND OTHER SITES OF EARLY MODERN EXPERIMENTATION

It is well known among historians that before the nineteenth century, naturalists and experimental philosophers performed experiments at many different sites that were not

[4] This fact has been pointed out in several publications. See, in particular, Maurice P. Crosland, "Early Laboratories, c. 1600–c.1800, and the Location of Experimental Science," *Annals of Science*, 2005, *62*:233–253; Owen Hannaway, "Laboratory Design and the Aim of Science: Andreas Libavius versus Tycho Brahe," *Isis*, 1986, *77*:585–610; Frank A. J. L. James, "Introduction," in *The Development of the Laboratory: Essays on the Place of Experiment in Industrial Civilisation*, ed. James (London: Macmillan; New York: American Institute of Physics, 1989), pp. 1–7; Steven Shapin, "The House of Experiment in Seventeenth-Century England," *Isis*, 1988, *79*:373–403; and Smith, "Laboratories" (cit. n. 2).

[5] To give one example from the early nineteenth century, before ca. 1850 the founder of the well-known German pharmaceutical company Merck, Heinrich Emanuel Merck, used the label "Chemisches Laboratorium von E. Merck in Darmstadt" for his pharmaceuticals.

[6] Denis J. Diderot and Jean LeRond d'Alembert, *Encyclopédie, ou dictionnaire raisonné des sciences, des arts, et des metiers*, 35 vols. (Paris, 1751–1780; rpt., Stuttgart: Frommann, 1966), Vol. 9, p. 145; Johann Heinrich Zedler, *Grosses vollständiges Universal Lexicon aller Wissenschafften und Künste*, 64 vols. (Halle/Leipzig: J. H. Zedler, 1732–1750), Vol. 16 (1737), p. 30; and Johann Georg Krünitz, *Oeconomische Encyclopädie, oder allgemeines System der Land, Haus- und Staats-Wirthschaft in alphabetischer Ordnung*, 242 pts. (Berlin: J. Pauli and E. Litfaβ, 1773–1858), Pt. 58 (1792), pp. 47–48. Here and throughout this essay, all translations are mine unless otherwise indicated.

specifically designed and equipped for the purpose. They experimented, for example, in salons, meeting rooms, and lecture halls or in the open marketplace and fields. There is also no question that early modern experimental philosophers and naturalists other than chemists did perform explorative *experimental trials* in addition to demonstration experiments. But how could they get along without laboratories? Or were there functional analogues to the chemists' "laboratory" that were simply designated differently?

Good candidates for the latter are "physical cabinets," "physical theaters," observatories, and "anatomical theaters." Physical theaters, such as the famous one established in the seventeenth century at the University of Leiden, were primarily designated for the teaching of experimental philosophy and the demonstration of physical models and instruments. Likewise, anatomical theaters, which were models for the physical theaters, were mainly teaching institutions. Physical cabinets were, as a rule, places for collecting and preserving physical models and instruments; these could be borrowed for performing experiments elsewhere, mostly for the purposes of teaching and lecture demonstrations.[7] They were thus often linked with physical theaters through shared pedagogical goals and interests. Although some of the eighteenth-century anatomical theaters, physical theaters, and physical cabinets may occasionally have been used to perform explorative experimental trials, this was certainly not their main function. Observatories too may sometimes have been sites for experimental trials, say, on heat, magnetism, or electricity, in addition to their primary use for systematic astronomical observation. Hence, all four of these early modern academic institutions certainly facilitated, or contributed to, experimentation, but they were not purpose-designed and purpose-equipped for the explorative, intervening style of experimentation. Their functions overlapped to some extent with those of the laboratory but were by no means fully identical with them. The same is true for another group of experimental sites—namely, the shops of instrument makers, coffeehouses, and sites of engineering and advanced mechanical manufacture, which sometimes combined systematic observation and experimental trials with commercial production.[8] We need more detailed historical studies of the specific sites of eighteenth-century experimental trials and production of experimental phenomena and things, but I would hypothesize that none of the institutions I have just discussed was fully analogous to the "laboratory."

Most eighteenth-century experimental philosophers and naturalists who studied the mechanical movement of bodies, the effects of heat, magnetism, and electricity, or the circulation of the blood, respiration, and other physiological phenomena performed their experimental trials in any suitable room—and that room would be used for many other purposes as well. We may perhaps draw one conclusion from this fact that is not too sweeping: experimental systems, in the sense of complex systems of targets, instruments, materials, and sources of power that were mutually adjusted to each other and encouraged daily experimentation, had not yet come into being in late eighteenth-century experimental physics, physiology, and other areas of the emerging life sciences. By contrast, an

[7] On physical theaters see Gerhardt Wiesenfeldt, *Leerer Raum in Minervas Haus: Experimentelle Naturlehre an der Universität Leiden, 1675–1715* (Amsterdam: Royal Netherlands Academy of Arts and Science, 2002). On anatomical theaters see *ibid.*, pp. 122–130; and Harold J. Cook, *Matters of Exchange: Commerce, Medicine, and Science in the Dutch Golden Age* (New Haven, Conn.: Yale Univ. Press, 2007). On physical cabinets see Gerard L'E. Turner, *Scientific Instruments and Experimental Philosophy: 1550–1850* (Brookfield: Variorum, 1990); and Turner, "Eighteenth-Century Scientific Instruments and Their Makers," in *The Cambridge History of Science*, Vol. 4*: Eighteenth-Century Science*, ed. Roy Porter (Cambridge: Cambridge Univ. Press, 2003), pp. 511–535.

[8] See James A. Bennett, "Shopping for Instruments in Paris and London," in *Merchants and Marvels*, ed. Smith and Findlen (cit. n. 2), pp. 370–395; and Larry Stewart, *The Rise of Public Science: Rhetoric, Technology, and Natural Philosophy in Newtonian Britain, 1660–1750* (Cambridge: Cambridge Univ. Press, 1992).

eighteenth-century experimenter would hardly have been acknowledged as a "chemist" if it were doubted that he actually had access to a laboratory. Thus the eighteenth-century French chemist Pierre Joseph Macquer left no doubt that "whoever (therefore) would become a chemist, *must indispensably have a laboratory* furnished with the most necessary instruments for the practice of this science."[9] Why were laboratories indispensable to the chemists, whereas other groups of early modern experimenters could do without them? Early modern academic chemists needed laboratories for several reasons, both technical and epistemic. The early modern chemical techniques required many different kinds of furnaces, along with chimneys and water fountains and tons of wood or charcoal, which could not easily be moved around. The ubiquity of furnaces and the use of fire in the chemical laboratory further demanded precautions against damage by fire. Chemical operations also meant dirty handiwork yielding lots of smelly, corrosive, or poisonous products, and this meant that having a specific room for the purpose was more than a mere convenience. Furthermore, most chemical experiments combined different techniques, such as mixing, dissolution, precipitation, and subsequent distillation or sublimation; this required many different types of vessels, instruments, reagents, and auxiliary materials, which had to be stored somewhere. The same was true for hundreds of reaction products and raw materials; these substances also had to be carefully protected from humidity and corrosion. In addition to these technicalities, eighteenth-century chemists had established a continual, more or less daily style of experimentation, in contrast to the often-interrupted experimental trials and public demonstrations characteristic of the core area of experimental philosophy. This style of continual experimentation was rooted in a long historical tradition. It fitted the commercial goals inherent in this tradition (on which more below), as well as the predominant intellectual interests, questions, and objects of inquiry of the late seventeenth- and eighteenth-century chemists: the study of the multifarious world of material substances. In their experimental histories and chemical analyses, the eighteenth-century chemists studied one material substance after the other; this style of experimentation was in principle unbounded, not only because of the immense number of relevant substances but also because of the material productivity of chemical experimentation, which often yielded new reaction products that invited yet further exploration.[10]

THE SHARED MATERIAL CULTURE OF EIGHTEENTH-CENTURY ACADEMIC AND ARTISANAL LABORATORIES

Our overall picture of eighteenth-century experimentation has been significantly shaped by historians of physics and their emphasis on the emergence of experimental philosophy in the seventeenth century and of quantification and precision measurement in the Enlightenment. This picture accords with our knowledge of the laboratories and precision experiments of the most famous late eighteenth-century chemist, Antoine-Laurent

[9] Pierre Joseph Macquer, *A Dictionary of Chemistry, Containing the Theory and Practice of That Science; Its Application to Natural Philosophy, Natural History, Medicine, and Animal Economy: With Full Explanations of the Qualities and Modes of Acting of Chemical Remedies, and the Fundamental Principles, of the Arts, Trades, and Manufactures Dependent on Chemistry*, 2 vols., trans. James Keir (London: T. Cadell, P. Emsly & J. Robon, 1771), Vol. 1, p. 365 (emphasis added). On "experimental systems" see Hans-Jörg Rheinberger, *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube* (Stanford, Calif.: Stanford Univ. Press, 1997).

[10] On eighteenth-century chemists' predominant concern with material substances and on "experimental history" see Ursula Klein and Wolfgang Lefèvre, *Materials in Eighteenth-Century Science: A Historical Ontology* (Cambridge, Mass.: MIT Press, 2007).

Lavoisier, and of some other prominent chemical philosophers such as Joseph Priestley and Henry Cavendish. Clearly, these chemists equipped their laboratories with the most advanced and costly precision instruments of their time. Yet these laboratories were by no means typical. Our concern with these outstanding chemists has too often blinded us to the circumstances of the more ordinary, lesser-known eighteenth-century chemists, apothecaries, assayers, and other apprenticed or university-educated experts who contributed to chemistry by watching artisanal operations and performing experiments with quite mundane instruments such as retorts, beakers, phials, or crucibles. We ought not forget that Lavoisier was a wealthy financier of the *ancien régime* who could afford to purchase outstanding, expensive precision instruments from the most renowned instrument makers of Paris and that many chemists, who lacked the means to buy such instruments, complained that they were unable to repeat his experiments. When we focus on these ordinary chemists, examining the equipment of their laboratories and their experimental techniques, it becomes clear that our picture of early modern and eighteenth-century experimentation is, to say the least, strikingly incomplete.

We have seen that, well into the nineteenth century, the term "laboratory" referred to both "academic" and artisanal workplaces implementing chemical operations.[11] The language of the historical actors raises the question of whether it reflected some actual correspondence between academic laboratories and the pharmaceutical, metallurgical, and other artisanal laboratories. Pamela Smith has effectively argued that the alchemical laboratories (before ca. 1700) resembled the workshops of apothecaries, metalworkers, potters, and many other types of artisans. I would go a step further, to argue that throughout the long eighteenth century there was a strong correspondence between the material culture of academic-chemical and artisanal laboratories, including their architecture, instruments, vessels, materials, and manipulative techniques. The *main* purpose of the newly established academic laboratories certainly was inquiry into nature (and art), whereas the artisanal laboratories were *primarily* places of commercial production. But even if we highlighted the historical actors' goals and interests at the expense of their shared material culture, it would not be appropriate to assume that around 1700 the laboratory made a "transition from artisanal workshop to its place as a central 'site of science.'"[12] Apart from the fact that the alchemical laboratory was also a site of learned inquiry, we should expect that a wholesale transformation of an artisanal workplace into a scientific institution would somehow be reflected in the actors' language; we should then observe an increasingly narrow use of the term "laboratory" to denote only academic laboratories by the end of the eighteenth century. Yet exactly the opposite was the case. The term "laboratory" was increasingly used in the eighteenth century, to include, in addition to academic-chemical and pharmaceutical laboratories, workplaces in arsenals, metallurgy (assaying), mints, dye manufactories, porcelain manufactories, distilleries, and perfumeries. More historical studies are necessary to understand why the use of the term "laboratory" was extended in the course of the eighteenth century. But it should be noted that all kinds of workshops then designated as "laboratories" were sites of technological venture, of knack and innovation, as the many treatises and experimental reports on

[11] In the following, I use the term "academic laboratory" as shorthand to denote all types of laboratories, public and private, of university-educated, or "academic," chemists. Beginning in the seventeenth century, public "academic laboratories" were established at academies, universities, botanical gardens, and museums; in the eighteenth century many of the newly founded professional schools also established (chemical) laboratories, and at the same time the older tradition of private laboratories continued.

[12] Smith, "Laboratories" (cit. n. 2), p. 292.

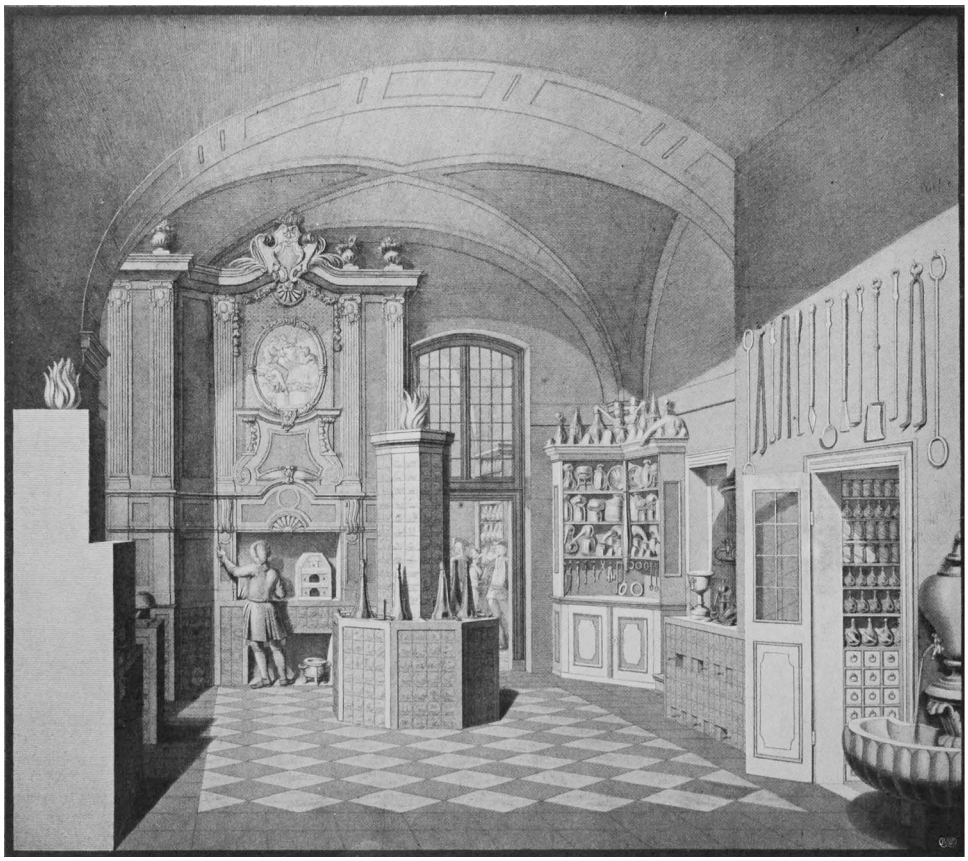

Figure 1. *The small laboratory of the Berlin* Hofapotheke *(eighteenth century), equipped with furnaces, a chimney, alembics, retorts, and other instruments. From Johannes Hörmann, "Die königliche Hofapotheke in Berlin (1598–1898),"* Hohenzollern-Jahrbuch*, 1898, pp. 208–226, on p. 224.*

fireworks, assaying, dyeing, the making of pigments, and the preparation of chemical remedies make clear.[13]

There was a particularly strong similarity between pharmaceutical and academic laboratories (see Figures 1 and 2). This can be easily seen when we compare drawings and instruments exhibited in today's pharmacy and science museums. The same types of furnaces, retorts, alembics, jars, beakers, phials, crucibles, and balances that chemists used in their laboratories were also used by apothecaries for the preparation of chemical remedies. Apart from drawings and preserved or excavated instruments, our knowledge of eighteenth-century laboratories also relies on inventories, verbal descriptions, and architectural plans. From these sources we know, for example, that the laboratories of eighteenth-century apothecaries and chemists were often established on the ground floor of a building and in rooms with vaulted stone ceilings. The former was particularly

[13] See Ursula Klein and Emma Spary, eds., *Between Market and Laboratory: Materials and Expertise in Early Modern Europe* (Chicago: Univ. Chicago Press, in press).

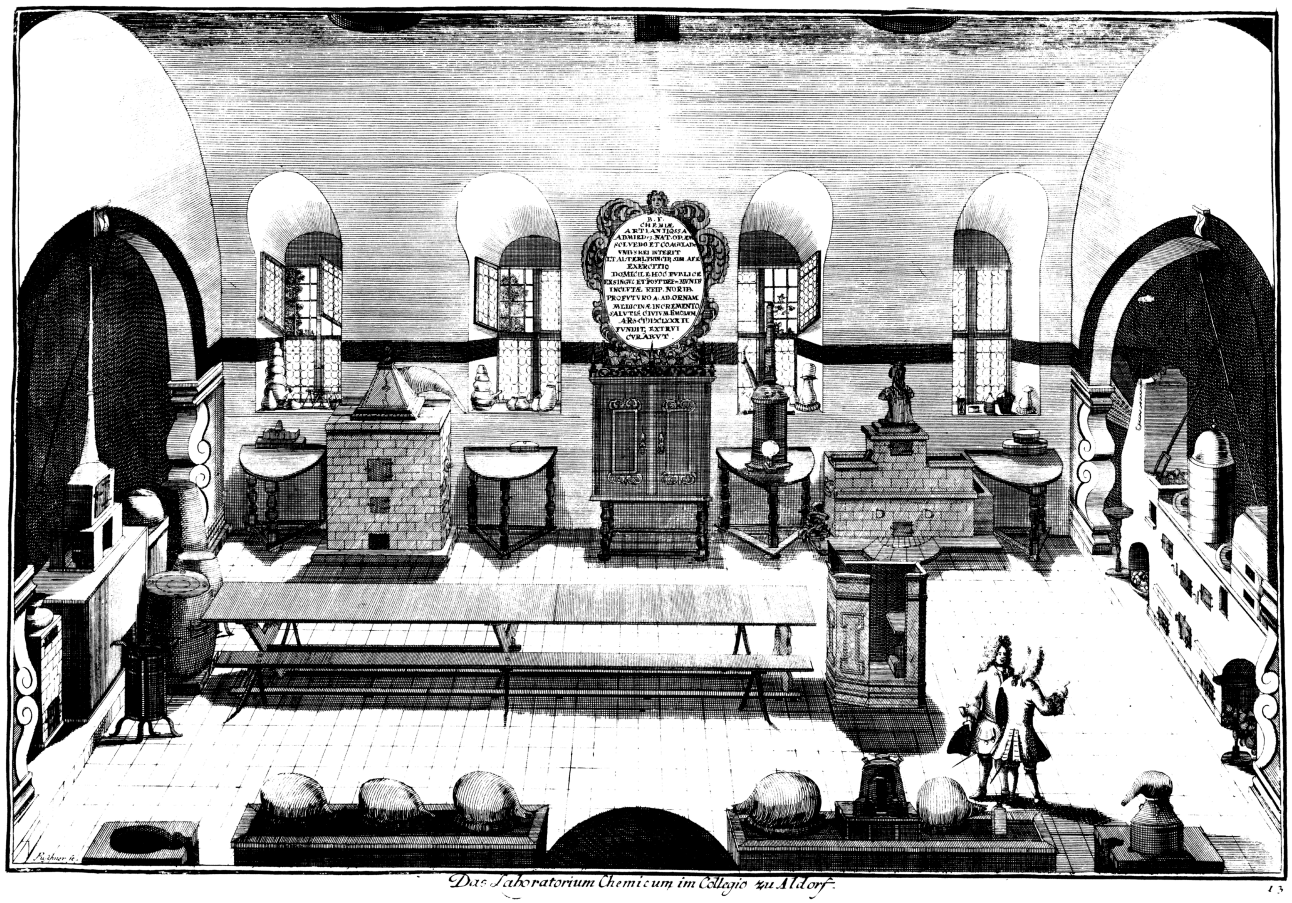

Figure 2. *The laboratory of the University of Altdorf, also dominated by chimneys, furnaces, and distillation vessels. From Johann G. Puschner,* Amoenitates Altdorfinae oder eigentliche nach dem Leben gezeichnete Prospecten der löblichen Universität Altdorf . . . *(Nürnberg: Michahelles, ca. 1720). Courtesy of the Niedersächsische Staats- und Universitätsbibliothek, Göttingen.*

convenient for supply with water and fuel; the latter meant protection against fire. Windows were very important for fresh air and to carry off poisonous vapors. The predominant equipment of both chemical and pharmaceutical laboratories was large furnaces, a chimney, and various kinds of distillation apparatus. Most of the substances used in the chemical laboratory, and subjected to experiments, were mundane commodities.[14]

The shared material culture of the pharmaceutical and academic-chemical laboratory helps explain why apothecaries frequently shifted from the commercial production of chemical remedies to careful observation and chemical analysis and why chemists moved between experimental analysis and pharmaceutical innovation. It explains why many eighteenth-century chemists were apprenticed apothecaries (approximately 50 percent of German chemists in the second half of the eighteenth century were apprenticed apothecaries; the rest were mostly university-educated physicians).[15] Observations and experiments performed in pharmaceutical and other artisanal laboratories contributed to chemistry well into the nineteenth century. Moreover, there was an impressive number of acknowledged "chemists" who performed their experiments in an apothecary's laboratory or some other artisanal laboratory. To give one example, the German chemist and apothecary Martin Heinrich Klaproth, discoverer of several chemical elements, not only analyzed hundreds of minerals in his pharmaceutical laboratory but also used the laboratory of the Royal Porcelain Manufactory in Berlin to perform mineral analysis.

I have scrutinized elsewhere the ways late eighteenth-century apothecaries produced chemical remedies in their laboratories and the smooth shifts they made from commercial production to systematic observation and experimental exploration of the properties and chemical transformations of material substances.[16] A particularly instructive case is the laboratory of the Prussian Academy of Sciences, founded in 1754 in the city of Berlin. This laboratory house, which included a residence for the laboratory's director, was equipped almost entirely with instruments, vessels, and materials from the pharmaceutical laboratory of its first director, the Berlin apothecary and chemist Andreas Sigismund Marggraf. There was, in this case, a direct transfer of material items from the artisanal to the academic laboratory, along with the elevation of an apprenticed apothecary-chemist to the status of director of an academic laboratory. The inventories of the academic laboratory further demonstrate that Marggraf's pharmaceutical laboratory was not better equipped than any other pharmaceutical laboratory located in a German city of the time. We must not conclude from the fact that the apothecary Marggraf was also a quite well-known chemist that he possessed a laboratory equipped with, say, electrical machines, air-pumps, and sophisticated precision instruments over and above the usual apothecary's balances. Instead, the first inventory of the laboratory, which included all

[14] For excavated laboratory instruments see Robert G. W. Anderson, "The Archaeology of Chemistry," in *Instruments and Experimentation in the History of Chemistry*, ed. Frederic L. Holmes and Trevor H. Levere (Cambridge, Mass.: MIT Press, 2000), pp. 5–34. On the substances used in eighteenth-century chemistry labs see Klein and Lefèvre, *Materials in Eighteenth-Century Science* (cit. n. 10).

[15] See Karl Hufbauer, *The Formation of the German Chemical Community (1720–1795)* (Berkeley: Univ. California Press, 1982).

[16] Klein, "Apothecary Shops, Laboratories, and Chemical Manufacture in Eighteenth-Century Germany" (cit. n. 2); Klein, "Die technowissenschaftlichen Laboratorien der Frühen Neuzeit" (cit. n. 2); Ursula Klein, "Apothecary-Chemists in Eighteenth-Century Germany," in *New Narratives in Eighteenth-Century Chemistry*, ed. Lawrence M. Principe (Dordrecht: Springer, 2007), pp. 97–137; and Klein, "Blending Technical Innovation and Learned Natural Knowledge: The Making of Ethers," in *Between Market and Laboratory*, ed. Klein and Spary (cit. n. 13).

items taken from Marggraf's pharmaceutical laboratory in order to reimburse him, listed very ordinary instruments and vessels such as portable furnaces, crucibles, retorts, phials, pots, sugar jars, bottles, bowls, tables, and chairs as well as chemical preparations and materials.[17]

The subsequent curious development of the Berlin academy's laboratory further illuminates the interconnectedness of artisanal and academic laboratories. In 1782, after Marggraf's death, Franz Carl Achard—a self-trained chemist and technical expert who would later become famous for the first extraction of sugar from beets on a large technological scale—succeeded him. In 1799 Achard received permission to use the academic laboratory as a "sugar factory"—that is, as a technological station to extract sugar from tons of beets. He removed the ordinary chemical instruments and instead installed large pots, pans, and copper boilers for the chemical purification and evaporation of the beet juice. As his experiments were promising, he left the academy some two years later to establish a sugar beet factory on his estate in Silesia, with the financial support of the Prussian king. When the apprenticed apothecary and chemist Heinrich Martin Klaproth was named director of the academy laboratory and sought to move into his new residence and laboratory house, he found that the house was rotting owing to the heavy production of beet sugar during Achard's tenure. After many complaints, a new laboratory was constructed for him; it was ready by the end of 1802.[18] When Klaproth moved in, he was in exactly the same situation as Marggraf roughly half a century before: he equipped the newly constructed academic laboratory with the instruments, vessels, and materials from his own pharmaceutical laboratory.

The laboratories of the Enlightenment were heirs of a long tradition, going back to medieval alchemy, that combined the commercial production of materials with learned inquiry into nature (and sometimes also with religion). Well into the nineteenth century, there were no *major* changes in the shared material culture of academic and artisanal or proto-industrial laboratories.[19] This does not mean that the laboratory equipment did not change at all in the course of the eighteenth century. The intellectual discontinuities between alchemy and eighteenth-century chemistry clearly had a counterpart in the laboratory. Thus alchemical instruments traditionally used for long circulations, maturations, and the transmutation of substances, such as the pelican and the philosophical egg, were discarded, as were these alchemical techniques themselves. Furthermore, from the middle of the eighteenth century chemists experimented more frequently with different kinds of air, using new pneumatic apparatus, and they slowly implemented new kinds of precision instruments. The famous chemical dictionary compiled by Macquer manifests these innovations. Whereas the first edition (1766) is silent about air-pumps, thermometers, pneumatic apparatus for collecting gases (or "kinds of air"), and other philosophical instruments, in the second edition, published in 1778, all of these are mentioned.[20] My argument is that the equipment of eighteenth-century laboratories with new kinds of

[17] Archive of the Berlin-Brandenburgische Akademie der Wissenschaften, Bestand Preu*β*ische Akademie der Wissenschaften (1700–1811), I–XIII-20, fols. 1–4.

[18] For the permission granted Achard see *ibid.*, I–XIII-26, fol. 1; on Klaproth's new lab see *ibid.*, I–XIII-26, fol. 131. On Achard see also Hans-Heinrich Müller, *Franz Carl Achard (1753–1821): Biographie* (Berlin: Bartens, 2002).

[19] See also Frederic L. Holmes, *Eighteenth-Century Chemistry as an Investigative Enterprise* (Berkeley: Univ. California Press, 1989), p. 18; and Ernst Homburg, "The Rise of Analytical Chemistry and Its Consequences for the Development of the German Chemical Profession (1780–1860)," *Ambix*, 1999, *46*:1–31, esp. p. 6.

[20] Pierre Joseph Macquer, *Dictionnaire de chimie, contenant la théorie et la pratique de cette science, son application à la physique, à l'histoire naturelle, à la médicine et aux arts dépendans de la chimie*, 2nd ed., 2 vols.

instruments proceeded in small steps, engendering differences in degree rather than a conspicuous bifurcation into separate artisanal and scientific types of laboratory.

SOME CONSEQUENCES

The sparse literature on the early history of the laboratory has long portrayed it as an institution that was, in Owen Hannaway's words, "indicative of a new mode of *scientific* inquiry."[21] In his celebrated essay "The House of Experiment in Seventeenth-Century England," Steven Shapin also defined laboratories as unambiguous sites of scientific experimentation. Although he took into account the existence of alchemical laboratories, he argued that the space for the new experimental philosophy "did not then clearly exist"; instead, it "had necessarily to be carved out of and rearranged from existing domains of accepted public and private activity." Shapin did not, however, identify the seventeenth-century alchemical laboratory as such an "existing domain"; rather, he focused on "the gentleman's private residence and, within it, its public room."[22] With this move, he wanted to highlight the production of factual knowledge and public witnessing as the hallmarks of the new experimental sciences—in puzzling agreement with the traditional epistemological focus on laboratories and experiments as the new "experimental method" of natural philosophy. Shapin rightly observed that a significant part of alchemical laboratory practice, in England and elsewhere, was secret—namely, the attempts to transmute base metals into gold; this part of alchemy was indeed not a model for the early modern experimental sciences. Yet epistemic openness did exist in many other areas of alchemical laboratory practice. Moreover, even the secret alchemy of gold making contributed to the development of experimental techniques and the material culture of the laboratory. Shapin's dismissal of the alchemical laboratory as a significant site of early modern experimentation, and its replacement by the gentleman's residence, relies on two closely related presuppositions that I have questioned here. The first is that epistemic values and methods must be the *crucial* criteria for our historical analysis of early modern experimentation and that material culture is less important; indeed, Shapin's argument is not based on any comparative analysis of the material culture of laboratories. The second presupposition is that "laboratories" were unambiguously sites of experimental philosophy and not also sites of technological innovation and commercial production.

I argue here for a different view. If the laboratory is to be taken as an emblem of something, that "something" is certainly not "experimental philosophy" or natural knowledge *per se*. For a truly historical understanding of the laboratory sciences, we must give up the narrow epistemological focus on the experimental sciences, as well as the view that the early modern sciences were concerned only with nature as something given. Like modern engineering and twentieth-century technosciences such as biotechnology, nanotechnology, or the materials sciences, the early modern laboratory produced not only knowledge, let alone knowledge about an immutable nature, but also artifacts and things (such as material substances). The specificity of the institution, especially the correspondence between the artisanal and academic laboratory, should be taken as an incentive to study the question of how experimental inquiry into nature was interconnected with technological innovation and the economic system of labor more broadly. The early

(Paris: L'Imprimerie de Monsieur, 1778), Vol. 2, pp. 1–9. On the changes from the middle of the century see Holmes and Levere, eds., *Instruments and Experimentation in the History of Chemistry* (cit. n. 14).

[21] Hannaway, "Laboratory Design and the Aim of Science" (cit. n. 4), p. 585 (emphasis added).

[22] Shapin, "House of Experiment in Seventeenth-Century England" (cit. n. 4), pp. 386, 397.

modern laboratory was the outcome of a long tradition in which innovative forms of labor, technical expert knowledge, and text-based philosophies developed in tandem.[23] It stands for one distinctive strand of this tradition that evolved around the making of materials and techniques like distilling, smelting, and dissolving, as employed in areas such as alchemy, metallurgy, pharmacy, gunnery, and pottery. Similar strands of the tradition developed in areas such as military engineering, architecture, ship building, the medical professions (especially surgery and anatomy), the cultivation of medical gardens and botany, the making of instruments, and mathematics. In all of these practices, handiwork was tied to some forms of advanced expertise, including text-based knowledge.[24]

In other words, the ancient separation of hand and mind, highlighted by Shapin, was restructured and slowly abolished in this mixed expert tradition. As early as around 1600, the humanist and physician Andreas Libavius had to defend himself against accusations that he did not possess a laboratory—and hence had no authentic knowledge about chemistry.[25] By the late eighteenth century, there was still a large faction of scholars who despised manual labor. Yet this group of traditional scholars was then counterbalanced by powerful groups consisting of members of academies and university-based anatomists, chemists, experimental physicists, cameralists, and technologists (*Technologen* in Germany), as well as school-based engineers, mining officials, assayers, pharmacists, and other types of hybrid experts. These hybrid experts, fostered by mercantilist states, argued emphatically in favor of an amalgamation of experimentation, hands-on knowledge, mathematics, and conceptually driven analysis that partly relied on knowledge transmitted by texts, diagrams, and other forms of representation.[26] Shapin's emphasis on the differences between early modern philosophers and "invisible technicians," along with his argument that the distinction between the philosophers' "knowledge" and the technicians' "skill" was "a particular version of such pervasive cultural divides as theory-practice, contemplation-action, and head-hand," oversimplifies epistemological constellations; it ignores what was by then a long-developing group of hybrid experts who bridged the gap between the intuitive, local knowledge of apprenticed craftsmen and the rational, text-based knowledge of university-educated scholars.[27] "Invisible technicians" like Robert Hooke belonged precisely to this third group of experts. There were many types of hybrid expert in the seventeenth and eighteenth centuries, who possessed both "knowledge" and "skill," and I have treated them here as one "tradition" simply so as to distinguish them from the more familiar traditions of scholars and craftsmen. The group included fireworkers, assayers, mining officials, goldsmiths, comptrollers of dye manufactories, apothecaries, surgeons, distillers, perfumers, and merchants; many physicians, instrument makers, and artists; and the majority of chemists, engineers, architects (*Baumeister*), mathematicians, and mineralogists. All of these experts were venturesome practitioners and literate

[23] Some alchemical laboratories were also sites of religious revelation; see Smith, "Laboratories" (cit. n. 2).

[24] See, e.g., the essays included in Roberts *et al.*, eds., *Mindful Hand* (cit. n. 2).

[25] See Bruce T. Moran, *Andreas Libavius and the Transformation of Alchemy: Separating Chemical Cultures with Polemic Fire* (Sagamore Beach, Mass.: Watson, 2007), pp. 54, 91.

[26] I argue that a significant part of these experts' knowledge was underdetermined by observation and experiments or local practice; I thus disagree with the sensualistic conceptions of those historians who identify all knowledge of these experts with gestural knowledge, tacit knowledge, skill, and so on.

[27] Steven Shapin, *A Social History of Truth: Civility and Science in Seventeenth-Century England* (Chicago: Univ. Chicago Press, 1994), p. 361; see also Lissa Roberts and Simon Schaffer, "Preface," in *Mindful Hand*, ed. Roberts *et al.* (cit. n. 2), pp. xiii–xxvi. It should be noted that my argument therefore also differs from the older craftsman-and-scholar thesis, developed by Boris Hessen, Henryk Grossmann, and Edgar Zilsel.

men (and a few women), and many of them were also authors of texts, machine drawings, naturalistic paintings, and other representations of nature and art.[28]

Historians have long discussed the relation between early modern experimentation and useful knowledge. In an earlier Focus section in *Isis*, Peter Dear argued that in the early modern period "natural philosophy came to be rearticulated (most famously by Francis Bacon) as involving both contemplative and practical knowledge." As a result, the scholarly philosophical tradition acquired a "systematic ambiguity," and tensions arose between a "discourse" of contemplative knowledge and a "discourse" of useful, instrumental knowledge. In other words, Dear understands the early development of the experimental sciences as a process of restructuring and reorientation that took place only within the context of a scholarly philosophical discourse; in this process of philosophical reformation, the traditional contemplative dimension of natural philosophy (i.e., learned men striving to understand and interpret nature) was preserved, and at the same time a new, but no less philosophical, experimental enterprise came into being: experimental philosophy. This new experimental philosophy was further linked to social and political reform movements and their utilitarianism—that is, to the idea, or ideology, that experimental effects and natural philosophy's explanatory principles could be put to practical uses.[29] Given this unequivocal understanding of useful knowledge as knowledge produced in the context of natural philosophy and as part of an ideology, it is a logical consequence critically to question the actual usefulness of that philosophical knowledge.[30] If, in addition, all types of artisans and craftsmen are conceived as one homogeneous group that lacks "intelligibility," it is natural that one would see a huge gap between an intelligible philosophical discourse, instrumental or contemplative, and the alleged world of techniques and unarticulated knowledge of artisans and craftsmen; "useful knowledge" then is just wishful thinking.[31]

The early history of the laboratory teaches a different lesson. We ought to replace the simple distinction between scholarly and artisanal knowledge by a richer taxonomy that does justice to the historical actors' mediation between these two extremes and the existence of a broad spectrum of forms of knowledge, with differences only in degree. The mediating tradition of hybrid experts, highlighted above, developed new forms of useful knowledge present neither in the tradition of scholars nor in that of ordinary craftsmen. These ranged from ineffable bodily skills to connoisseurship of materials, tacit and verbal, to articulated know-how, to methods of measuring, data gathering, and classification, all the way to conceptually driven analysis and work on paper using various kinds of paper tools to construct intelligible representations. And these different forms of useful knowledge were often developed in the course of technical ventures and innovative making practices. The laboratory—academic and artisanal—stands for an experimental tradition and a group of experimenters who did not merely muse and debate about the possible

[28] On this group's ways of representing see, in particular, Wolfgang Lefèvre, ed., *Picturing Machines: 1400–1700* (Cambridge, Mass.: MIT Press, 2004); Pamela O. Long, *Openness, Secrecy, Authorship: Technical Arts and the Culture of Knowledge from Antiquity to the Renaissance* (Baltimore: Johns Hopkins Univ. Press, 2001); and Pamela H. Smith, *The Body of the Artisan: Art and Experience in the Scientific Revolution* (Chicago: Univ. Chicago Press, 2004).

[29] Peter Dear, "What Is the History of Science the History Of? Early Modern Roots of the Ideology of Modern Science," *Isis*, 2005, *96*:390–406, esp. pp. 390 (quotation), 395.

[30] For a criticism of this unilinear model see also Roberts and Schaffer, "Preface" (cit. n. 27), p. xviii.

[31] Peter Dear, "Toward a Genealogy of Modern Science," in *Mindful Hand*, ed. Roberts *et al.* (cit. n. 2), pp. 431–452, esp. p. 435 f.

usefulness of learned knowledge but had long been putting useful knowledge into action by making things and improving techniques and materials.[32]

Dear argues convincingly that the early modern natural philosophers adopted a new experimental, or instrumental, approach to nature and at the same time preserved the contemplative, or theoretical, dimension of natural philosophy. But I would add that this is not the whole story. Early modern experimentation was by no means a unified philosophical enterprise; it was not merely the result of a transformation of a philosophical, or scholarly, tradition.[33] Putting it plainly, one might state that a second tradition of experimentation began to flourish in the seventeenth century, in addition to "experimental philosophy," that was tied to and developed in laboratories, artisanal and academic.[34] Beginning in the seventeenth century, this second experimental tradition was integrated into academic institutions—along with the entire mixed expert tradition of innovative making and knowing—and was thereby elevated to a higher social and cultural status. The institutionalization of laboratories at late seventeenth- and eighteenth-century medical faculties, academies, and scientific societies, fostered especially by mercantilist states, did not, however, replace the institution of the artisanal laboratory. This process was, rather, a diversification in which laboratories were "elevated" to academic institutions and at the same time further developed in areas of commercial production and technological innovation.

[32] It should be noted that in the tradition of Aristotelian philosophy, making practices were defined as "poiesis" and thus demarcated from both "theory" (or contemplation) and "practice."

[33] My argument can be extended more broadly to the early modern sciences, of which the experimental sciences were a significant part. By contrast, in a recent Focus section in *Isis* Michael Friedman observed the following "stubborn historical fact": "For it is simply a historical fact—and a particularly stubborn one—that modern science and philosophy first came into being as an inseparable unity." Michael Friedman, "History and Philosophy of Science in a New Key," *Isis*, 2008, *99*:125–134, on p. 129. Several historians of science have questioned this view from another perspective than experimentation; they have argued that medicine (including anatomy and physiology), mixed mathematics (including astronomy, optics, and hydrostatics), mechanics, and natural history were loosely linked with early modern natural philosophy but not subunits of it. See, e.g., Katharine Park and Lorraine Daston, "Introduction: The Age of the New," in *Cambridge History of Science*, Vol. 3, ed. Park and Daston (cit. n. 2), pp. 1–17.

[34] It should be noted that talk about a "second tradition" is a simplification, as it obliterates interactions between these two experimental strands.