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Wolfgang Lefèvre

Minerva Meets Vulcan: Scientific and Technological Literature – 1450–1750

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Contents

Chapter 1
Introduction

1.1 Science and Technology

This book investigates the relations between the developments of technology and science in the West in the early modern era, that is, the period from the late Middle Ages up to the eighteenth century. It investigates these relations – ranging from those between unrelated parallel courses of development to several forms of interplay and exchange, and then to forms of partial blending – as they are manifested both in the scientific and technological literature.

As we know, speaking of "science" and "technology" in relation to the early modern age is somewhat anachronistic and needs clarification at the outset. As regards "science," it has been shown that modern natural science, which is developing as an increasingly differentiated totality of scientific disciplines, did not emerge until the period from the mid-eighteenth to the mid-nineteenth century. Before this formation of modern scientific disciplines, structures and laws of nature had been studied and conceptualized by and in the frame of traditional domains of learning, namely *natural history*, *mixed mathematics* (mechanics, hydrostatics, optics, astronomy, music theory, etc.) and particularly *natural philosophy*.[1] Thus, when speaking in the present book about the relations between science and technology in the early modern period, we specifically mean the relations of the latter to one of these premodern domains of learning.

As regards "technology," things are more complicated. The term, originally an ancient technical term referring to a systematic treatment of grammar and rhetoric, first came to mean knowledge of the arts only at the turn of the seventeenth century, that is, almost at the end of the period studied in this book. And it was not until 1777 that the German professor of economy Johann Beckmann (1739–1811) gave a more precise definition of the kind of knowledge indicated by "technology" (*Technologie*).

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[1] See, for instance, Cunningham and Perry (1993).

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Beckman used the term in the context of German cameralistic endeavors when advocating technology as systematically descriptive knowledge about materials, techniques, and tools employed in the arts and crafts of his time. Finally, in the course of the nineteenth century, and along with the continuing expansion of training facilities for aspiring practical experts, "technology" assumed the additional meaning of knowledge of the principles or laws utilized by these means of production. Only then did "technology" also refer to a special branch of science, the engineering sciences taught at technical universities.[2]

In accordance with the eighteenth-century meaning of the term "technology," in the following we will regard such early modern literature as "technological literature" that transmits practitioners' or experts' knowledge about techniques, materials, and tools employed in the respective contemporary trades and industries.[3]

> Our focus on "technological literature," that is on "codified knowledge", means to exclude or ignore "embodied" knowledge to a certain degree – "embodied" knowledge about materials, techniques, and tools characteristic of the crafts, which accounts for a wealth of early modern technological knowledge.[4] In other words, excluded is an essential part of "practical knowledge", that is, as Jürgen Renn put it,
>
> *the knowledge resulting from the experiences of specially trained practitioners. It is generated from the pursuit of a special task or the use of specific tools and is characteristic of all kinds of craftsmanship […] It has been transmitted, for long historical periods, as part of the transmission of professional skills.*[5]
>
> In this book we will only address this knowledge if and insofar as it is part and parcel of advanced technological fields such as architecture or mining.[6]

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[2] Johann Beckmann: *Anleitung zur Technology, oder zur Kentniß der Handwerke, Fabriken und Manufacturen, vornehmlich derer, die mit der Landwirthschaft, Polizey und Cameralwissenschaft in nächster Verbindung stehn*. Göttingen: Vandenhoeck, 1777. Unlike in German and other European languages, a distinction between technique and technology did not exist in English. Rather, even today, the term can refer both to the techniques, processes, and tools used in the production of goods or services and to knowledge about these means of production. Furthermore, as regards the latter meaning, "technology" can simply refer to expert knowledge of some of these means or to the special case of the engineering sciences taught at technical universities. For the still unclear meaning of "technology" in English, see, for instance, Schatzberg (2006).

[3] For the problems as well as the requisite care in using the notion "expert" for historical actors of the early modern period, see, for instance, Ash (2019).

[4] For the notions of "embodied" and "codified" knowledge as well as for the significance of both for understanding technology-related knowledge in the early modern period, see, for instance, Popplow (2015).

[5] Renn (2020) 410.

[6] The significance of this practical knowledge, not only for the arts and crafts but also for advanced trades and industries and furthermore not least for "codified" technological knowledge, can hardly be overestimated. That is why the early modern artisan and his workshop became the subject of a rich literature in the last two or three decades. This literature covers the thematic spectrum from the general relationship between making and knowing, e.g. Marchand (2011), to specific practices of knowledge production, e.g. Smith and Schmidt (2008) or Dupré (2017), focuses on workshops as hotbeds of knowledge generation, e.g. Roberts et al. (2007), or on exemplary artisans, e.g. Smith (2004) or Nummedal (2007). In this book, we will refer to several aspects of this subject that concern the relationship between technological and scientific literature – see below Sect. 1.2 of this introduction.

The "codified" technological knowledge under investigation in this book, that is the early modern technological literature examined here, is not just craftsmen's knowledge written down. Rather, it differs from this "embodied" knowledge in several ways. First, its authors were very rarely craftsmen. They were usually persons familiar with advanced technologies that developed alongside – though not completely detached from – the world of ordinary crafts, such as mining, construction, weaponry, etc. In contrast to the oral instructions by which "embodied" knowledge was transmitted, technological literature – treatises, drawings, diagrams, mathematical tables, and so on – also imparted a more general, not locally confined "formalization" or standardization to the knowledge transmitted. This "codified" technological knowledge is, furthermore, of particular interest in view of the relationship between technological and scientific knowledge in the early modern period since it was open to incorporating rules (not theories) borrowed from fields of learned knowledge, e.g. from Euclidean geometry. In a mature stage it even facilitated attempts at conceptualizing the characteristics of materials, procedures, and tools employed in such advanced fields of production.

Among the several current definitions of "technology," one is of particular interest for our investigation because it addresses and directly fixes the relationship between science and technology by understanding the latter as an application of the former. To give some of the many possible examples: Technology is

- *the study and knowledge of the practical, especially industrial, use of scientific discoveries.* (Cambridge Dictionary)
- *the application of scientific knowledge for practical purposes, especially in industry.* (Lexico Oxford*)*
- *refers to methods, systems, and devices which are the result of scientific knowledge being used for practical purposes.* (Collins Dictionary)

True, these definitions refer to modern technological sciences, not to early modern technology. The linear model of the relationship between science and technology they presuppose was and is, however, usually taken as universally valid irrespective of its inapplicability to the early modern period. Up to the eighteenth century there were no scientific theories like nineteenth-century electromagnetism that practitioners could have "applied" and transformed into techniques and procedures or tools and other means of production. Moreover, in this historical period we usually encounter the opposite case that theories are conceptualizations of existing technical items. To give a classic example: The steelyard, the balance with unequal arms, was not an "application" of Archimedes' statics; rather, classical statics was a result of Archimedes' conceptualization of mundane devices like the steelyard.[7]

Apart from these historical considerations, this linear model can be and has been challenged as regards the relationship between modern technological and natural

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[7] See, for example, Lefèvre (2001) and Damerow et al. (2002).

sciences. Edwin Layton did this momentously half a century ago when he replaced the linear model with an "interactive model" (Channell) of science and technology.[8]

Layton saw the communities of science and technology that developed in the course of the nineteenth century as "mirror-image twins." As to the shared features of these *twins*, Layton emphasized the similarity of methods as well as of values and institutions in the natural and the technological sciences.[9] And as regards the differences between these *twins*, he emphasized particularly the different role played by fundamental theories on each side.[10] Accordingly, he conceived the relationship between the *twins* as a symmetric one on this level of development of science and technology and, indeed, advocated an interactive model of science and technology, arguing that "information can be transferred in either direction."[11]

Layton gave an example for his description of the *mirror-image twins*: the emergence of the engineering sciences in the United States in the last decades of the nineteenth century – a process he assessed as a "scientific revolution." "American technology," he wrote,

> *went through a scientific revolution in the 19th century. Technological knowledge was uprooted from its matrix in centuries-old craft traditions and grafted onto science. The technological community, which in 1800 had been a craft affair but little changed since the middle ages, was reconstructed as mirror-image twin of the scientific community.*[12]

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[8] Layton (1971). For the discussions of Layton's article, see, for instance, Channell (1989) and (2009).

[9] "The engineering sciences, by 1900, constituted a complex system of knowledge, ranging from highly systematic sciences to collections of 'how to do it' rules in engineering handbooks. Some, like the strength of materials and hydraulics, built directly on science; they were often classed as branches of physics. Others, such as the kinematics of mechanisms, evolved from engineering practice. In either case, their development involved the adoption by engineers of the theoretical and experimental methods of science, along with many of the values and institutions associated with their use. By 1900 the point of origin made little difference; the engineering sciences constituted a unity. Those derived from practice took on the qualities of a science in their systematic organization, their reliance on experiment, and in the development of mathematical theory. At the same time, sciences like the strength of materials gradually diverged from physics, assuming the characteristics of an autonomous technological science." (Layton (1971) 567f.)

[10] "In the case of mirror-image twins there is a subtle but irreconcilable difference which is expressed as a change in parity. Between the communities of science and technology there was a switch of values analogous to a change in parity. One way of putting the matter would be to note that while the two communities shared many of the same values, they reversed their rank order. In the physical sciences the highest prestige went to the most abstract and general – that is to the mathematical theorists from Newton to Einstein. Instrumentation and applications generally ranked lowest. In the technological community the successful designer or builder ranked highest, 'mere' theorist the lowest. These differences are inherent in the ends pursued by the two communities: scientists seek to know, technologists to do. These values influence not only the status of occupational specialists, but the nature of the work done and the 'language' in which that work is expressed." (Ibid. 576) Another noteworthy difference Layton pointed to concerns the implementation of mathematical methods. Whereas physicists normally admitted only rigorous mathematical methods, academic engineers relied more on approximations and less rigorous graphical methods.

[11] Ibid. 578.

[12] Ibid. 562.

Whether or not this statement applies to the history of "American technology," it certainly fails to hold true for the historical development of technology in Europe, where the technological community of 1800 was in no way just a "craft affair but little changed since the Middle Ages." This is well known in the case of France where the formation of modern engineering sciences was underway at the time. The famous *École polytechnique* in Paris was already 6 years old in 1800. Moreover, the foundation in 1794 of this central educational institution for aspiring engineers and other technical experts by Lazard Carnot (1753–1823) and Gaspard Monge (1748–1818) was a step in the reform of an already existing cluster of special engineering schools which had arisen since the turn of the sixteenth century and included several *Écoles militaires* (since 1719), the *École des ponts et chaussées* (founded in 1747), and the *École de mines* (founded in 1783).[13]

Less well known are similar developments in some German-speaking states in the second half of the eighteenth century, particularly in Prussia, Saxony, and the countries of the Hapsburg monarchy. Here, too, educational institutions were founded for training aspiring technical experts in various practical fields – mining academies in Freiberg (Saxony) and Schemnitz (in present-day Slovakia), a building academy (*Bauakademie*) and an industrial academy (*Gewerbeakademie*) in Prussia, etc. The main motive of these initiatives, which must be seen against the background of the cameralistic policy of several governments in continental Europe as well as of the emergent Industrial Revolution, was the increasing need for competent civil servants in the growing technical departments of the state bureaucracy. The view of science pursued in these endeavors was the concept of "useful sciences" (*nützliche Wissenschaften*).[14]

Ursula Klein has shown that the concept as well as the implementation of these useful sciences at the turn of the eighteenth century anticipated major features of Layton's engineering sciences. Not only was useful knowledge the ultimate aim of both but natural-scientific and technological inquiry were also interdependent or even converged in both cases since the objects of their inquiry overlapped. As regards research, the useful sciences organized research, established research laboratories, and picked up research methods from the natural sciences like Layton's engineering sciences a century later. Finally, the practitioners of both useful science and engineering science eschewed the type of high theory elaborated in natural philosophy and in physics, respectively.[15]

These beginnings of modern engineering sciences on the European continent in the course of the eighteenth century were certainly a milestone in the history of the fabric of sciences in the West – a milestone, not a "scientific revolution." In the eighteenth century, neither the French nor the Prussian technological community was "a craft affair but little changed since the middle ages," as Layton put it with

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[13] See, for instance, Belhoste (2003), Alder (1997), Picon (1992), and Aguillon (1889).

[14] For the Prussian building academy and the industrial academy, see, for instance, Dobbert (1899) and Kahlow (2000); for the mining academies, see Sect. 6.6 of the chapter on mining science.

[15] Klein (2020), esp. chap. 17.

regard to “American technology.” Thus, the incipient engineering sciences in France or Prussia did not and were not obliged to “uproot” the existent technology “from its matrix in centuries-old craft traditions and graft it onto science.” Rather, these beginnings of modern engineering sciences crowned technological knowledge and conceptions developed in connection with several new and advanced sectors of production alongside the ordinary crafts that had arisen since the fifteenth century. It is these developments and their relationship with learned/scientific knowledge that this book will investigate.

1.2 Practical and Learned Knowledge in the Early Modern Period

Among present-day historians of science, it hardly remains controversial that contact and exchange between educated and practical knowledge played a significant role in the development of the natural sciences and technology in early modern Europe. Several paths for such exchange arose from the late Middle Ages onward, notwithstanding the fact that large parts of the worlds of learning and mundane practices remained out of touch with each other up to the eighteenth century, as is notoriously the case for most of the scholarship cultivated at the universities as well as the majority of crafts. The emergence of more closely related developments in some fields of practical and learned knowledge was essentially facilitated by the formation of an economy of knowledge that fostered contacts and exchange between the two worlds.

As regards the notion of “economy of knowledge,” I follow Jürgen Renn, who has defined this economy as the “ensemble of practices and institutions by which societies produce and reproduce knowledge.”[16] The formation of this economy in the early modern period induced and was conversely shaped by several instances or entities mediating between educated and practical knowledge – *personae* (clerics, physicians, engineers/artists/architects, “hybrid experts,” etc.); *venues* (monasteries, courts, cities, “trading zones,” state administrations, etc.); *institutions of knowledge transmission* (apprenticeships, the journeyman system, schools, academies, etc.); *media of knowledge transmission and exchange* (oral instruction, travelling, manuscripts, printed texts, pictures, diagrams, tables, etc.). Several aspects of these instances are of particular interest for our investigations and should therefore be briefly addressed.[17]

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[16] See Renn (2020), chap. 8, especially p. 143.

[17] Each of the four instances of the early modern economy of knowledge – *personae*, *venues*, *institutions of transmission*, and *media* – merit portrayal in a chapter of their own or even a book. In this introductory chapter we must confine ourselves – except for the discussion of one controversy – to some key words and facts of particular interest for our investigation topic without going into details of the literature. As far as I know there are no suitable monographs on any of these instances that could be recommended for “further reading.”

(1) As regards *personae*, a rich literature on this topic appeared in the last two or three decades. I will not discuss this further here.[18] Instead, I will recall a highly charged ideological controversy of the 1950s, at the height of the Cold War, about the role of artisans and scholars in the Scientific Revolution – the controversy over the "Scholar-and-Craftsman" thesis. In this controversy, A. Rupert Hall had rightly criticized the view "that sees the new scientist of the seventeenth century as a sort of hybrid between the older natural philosopher and the craftsman."[19] This view had, however, never been advocated by Robert Merton, Hall's chosen target in his campaign against vulgar Marxist narratives of the history of science and particularly of the Scientific Revolution which, in Hall's view, ought to be seen as the "formation of the modern scientific attitude" characteristic of the West.[20]

This controversy is recalled here because of Merton's accurate view of the interchange between learned and practical knowledge in the early modern period, which can be taken as a point of departure for our investigations. Merton was not thinking of ordinary craftsmen when speaking of exchanges between learned men and practitioners but of a very specific group of practitioners – a group that will figure prominently in this book: engineers, gunners, land surveyors, instrument makers, and the like: technical experts who distinguished themselves from ordinary craftsmen not only by their special practical knowledge but also by their investigative ambitions and enterprises.[21] And as regards the counterparts of these experts, Merton was not thinking of traditional "scholars," but rather of men of the incipient modern sciences, who approached technical experts and inventors and emphasized the role played by experience in the acquisition of knowledge.

Moreover, Merton also noticed the occasional hybridization of the roles of the practical expert and the scientist, that is the emergence of the figure of a hybrid scientist and inventor or, as described and conceptualized by Ursula Klein, the "hybrid expert."[22] It may be mentioned in passing that, while such hybrid experts were rather the exception among technical experts before the eighteenth century, one finds hardly any of the renowned early modern scientists – be it Johannes Kepler (1571–1630) and Galileo Galilei (1564–1642) or Isaac Newton (1643–1727) and Gottfried Wilhelm Leibniz (1646–1716) – who did not also dedicate himself to technological problems.

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[18] For this literature, see, for instance, Popplow (2015).

[19] A.R. Hall (1959) 17; see also A.R. Hall (1963). Hall did not deny contacts and exchanges between learned men and practitioners in the early modern period but regarded them as fairly insignificant for the rise of the modern sciences, which he saw developing autonomously according to their own laws.

[20] A.R. Hall (1954). Hall's critique was directed against Merton (1938). In the ensuing debate, other suspects of vulgar Marxism besides Merton came into the firing line, e.g. Edgar Zilsel, Boris Hessen, or Henryk Grossmann. For the Scholar-Craftsman controversy and its background, as well as for the following, see Klein (2020) 231ff.

[21] For these experts and their significance for the new sciences, see also Long (2011).

[22] See Merton (1938) 146. For the notion "hybrid expert," see Klein (2017).

These scientists and technical experts are certainly the most important but not the only actors of an increasingly mutual openness between learned and practical knowledge in the early modern economy of knowledge, as we will see below in connection with the media of knowledge transmission and exchange.

(2) As regards *venues* where learned men or, later, scientists and practitioners could meet, establish and maintain contacts, and share mutual interests, a whole spectrum of such opportunities for encounter developed during the early modern period. At the end of the Middle Ages, flourishing cities like Ghent, Florence, or Nuremberg provided such venues in the form of artists' workshops and municipal institutions and became cultural centers alongside university cities. Beginning around 1500, a growing number of absolutist rulers sought to raise the prestige of their courts by inviting and engaging learned men and excellent practitioners competent in civil projects as well as warfare. It may suffice just to name the courts of the Montefeltro in Urbino, the Medici in Florence or Emperor Rudolph in Prague.[23]

Another venue of learned and practical knowledge was offered by sites of advanced technologies. These venues were certainly less splendid than princely courts but probably more momentous for the development of science as well as technology. Georg Agricola (1494–1555), for example, when working as a mining physician in one of the centers of silver mining, studied the technologies of mining and smelting and published his findings in a work that became the standard reference on these topics for the next 200 years. It goes without saying that he could accomplish this work only by intensive exchange with practical mining and smelting experts. Irrigation and drainage of mines as well as of marshlands was another advanced technology which attracted hybrid experts like Simon Stevin (1548–1620) or renowned scientists like Leibniz who experienced the difficulties one encounters in communication between learned and practical knowledge. Another example is Galileo's dealings with the Arsenal of Venice, which also entailed embarrassing misunderstandings.[24]

Among the workplaces that became such venues in the early modern period, the workshops of instrument makers deserve particular attention. They were meeting points of various kinds of practical mathematicians – astronomers, mathematical geographers, cartographers, surveyors, pilots and navigators – including several hybrid experts who were ideal mediators between the worlds of learned and practical knowledge.[25] Similar effects involved large practical mathematical projects like the mapping of an entire big city achieved in cooperation with various kinds of practitioners and educated men. Such cooperations worked well as "trading zones" between the professionals of these two different worlds.[26]

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[23] For the European courts of the early modern period, see, for instance, Adamson (1998) and Elias (1983).

[24] See the chapters below on mining and mechanical engineering.

[25] For mathematical instruments, instrument makers, and practical mathematics in the early modern period, see, for instance, Damerow and Lefèvre (1985) and Bennett (1987).

[26] For the notion of "trading zones," see Long (2012).

Finally, in the seventeenth and eighteenth centuries, venues of exchange between scientific and technological expertise even assumed an institutional form, namely in the new academies of science.[27] As is well known, the first of these early modern academies, the Florentine *Accademia del Cimento* (founded in 1657), was an institution in which practical experts with or without an academic background cooperated in scientific investigations undertaken by the academy. Probably less well known is that the famous academies of science of Paris and London, also founded in the seventeenth century, as well as their later counterpart in Prussia, admitted as members experts in various practical fields without an academic training. These experts cooperated (and competed) with the learned members in assessing proposed projects for the government as well as in genuine scientific investigations.

(3) As regards *institutions of knowledge transmission*, the educational institutions organizing the transmission of learned and practical knowledge were largely separate from each other from the Middle Ages up to the eighteenth century and beyond. As a rule, learned knowledge was taught at the universities, while practical knowledge was transmitted by the system of apprenticeship and travelling journeymen. Technical experts such as architects, engineers, mining officials and so on acquired their practical knowledge and expertise principally in the same way as master craftsmen – by apprenticeship, travelling, exchange with other experts, and participation in or coordination of extraordinary projects. As we have seen above, sustained educational institutions for teaching sophisticated technological knowledge came into being only in the late seventeenth and the eighteenth centuries.

As is well known, a general school education did not exist in this period. However, as early as in the High Middle Ages, there were a few places where some schooling of practitioners was established, for example in Italy where *Abacus Schools* transmitted basic mathematical knowledge for merchants and some craft professionals. These schools were established in some cases by city authorities, mostly however by private teachers, the arithmeticians or reckoning masters (*Rechenmeister*). After the advent of printing, books or booklets provided practitioners and an interested public with mathematical or other knowledge, that is, texts that facilitated self-study.[28]

Self-study and autodidactic appropriation of learned knowledge compensated for the lack of schools and other institutions of knowledge transmission besides the universities. This must be regarded as an essential feature of knowledge transmission in the early modern period. The proficiency of engineers, architects, and particularly of practical mathematicians in mathematics and sometimes even in classic texts and theories remains inexplicable otherwise. The engineer-artist Leonardo da Vinci (1452–1519) is certainly the most prominent of these autodidacts. The more or less successful efforts of the architect and engineer Francesco di Giorgio Martini (1439–1501) or the practical mathematician Niccolò Tartaglia (1499–1557), both of

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[27] For early modern academies of science, see, for instance, Feingold and Giannini (2020).

[28] See Sects. 7.2 and 7.3 of the chapter below on practical mathematics.

whom lacked university education, in translating and editing texts by Vitruvius, Euclid, and Archimedes show how ambitious Renaissance autodidacts could be.[29]

(4) As regards the *media of knowledge transmission*, the significance of media for the transmission of knowledge appears in a new light against the background that almost no school education existed in the early modern period. Yet an increasing demand for all kinds of knowledge was aroused at the turn of the fifteenth century by the developments of extended commerce, new trades and technologies, geographical discoveries, and so on. This led, on the basis of the newly invented art of printing, to a boom in practical books – such as booklets on basic mathematics for practitioners, gunners' manuals, *Books of Secrets*, *Probier*- and *Destillierbüchlein*, etc.[30]

Ordinary craftsmen are rarely found among the authors of such books but there are plenty of artists, engineer-artists, practical mathematicians, instrument makers, etc. and, particularly in the sixteenth century, physicians. Many publishers also acted as "authors," since not a few of these practical books were compilations of sections or parts of earlier books or even – according to today's standards – outright plagiarisms which was not yet generally condemned at the time. In view of the transmission of knowledge, such compilations or plagiarisms should not be dismissed; they were, like translations, no less important and sometimes even more effective transmitters of knowledge than the respective original publications.

Finally, it should not be forgotten that books – manuals, instructions, treatises – were not the only media of knowledge transmission but also drawings, plans, or diagrams. Practical knowledge could also be transmitted by presentational documents – advertisement of inventions, project proposals, or inventories. The famous early modern theaters of instruments and machines must be included here as well as their "real" counterparts, that is, arsenals and other collections of devices and/or models of devices – collections that had sometimes been established and classified especially for didactic purposes.

Summing up this section, we can state that the early modern economy of knowledge in its various dimensions brought forth a cluster of favorable conditions for interrelations between learned and practical knowledge. Moreover, when looking back from the eighteenth century to the late Middle Ages, a certain progressive development of such favorable conditions seems unmistakable. Printed texts and images succeeded manuscripts; practical booklets were followed by manuals, treatises, and textbooks on technological issues; sites of advanced technologies and, later, academies succeeded princely courts as major venues for educated men and

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[29] By the way, most of the knowledge these men sought could not be obtained in the universities of the time.

[30] For these practical booklets, see Ferguson (1959) and Eamon (1994) as well as Sects. 3.1, 3.2 and 3.3 of Chap. 3, Sects. 4.2 and 4.4 of Chap. 4, and Sect. 7.3 of Chap. 7. – Eamon saw a connection between the broad interest in this sixteenth-century practical or how-to literature and the later efforts of systematically studying the technology employed in the arts and crafts as prominently advocated by Francis Bacon (1561–1626) and other seventeenth-century promoters of a new learning. For Bacon's idea of a "history of trade," see, for instance, Houghton (1941).

technical experts; learned knowledge was no longer the exclusive possession of traditional scholars; and university trained engineers and architects like Bernard Forest de Bélidor (1698–1761) took the place of autodidacts like Francesco Giorgio Martini or Leonardo da Vinci.

No wonder the West was (and is) proud of these developments and saw them, and particularly the Scientific Revolution, as evidence that rationality and sober empiricism, Rupert Hall's "modern scientific attitude," were the basis and guarantees of the success (and alleged superiority) of the West. The current debates about the Great Divergence pivoting around the question "Why Europe?" rightly remind us of the fact that several civilizations in history achieved comparable peaks of scientific and technological accomplishments even though, for a variety of reasons, they proved unable to stabilize and sustain this advanced level.[31] Focusing as we do in this book on science and technology alone, it is hard to see why eighteenth-century Europe could have been more successful in this respect.[32] Whatever the case, our focus is on the development of scientific and practical knowledge up to the level achieved in the eighteenth century and, more specifically, on the interrelations between these two domains of knowledge in the course of this development.

1.3 The Book's Questions and Approach

If one takes the *École polytechnique* in France or the *nützlichen Wissenschaften* pursued by the Prussian state administration in the second half of the eighteenth century as beginnings and early instances of the modern relationship between science and technology which Layton conceived of as the relationship of *mirror-image twins*, how can one account for the emergence of such early institutions? Did they result from a "scientific revolution" or were they, as we will see in the following, the fruit of a long and meandering development of interrelations and exchanges between learned and practical knowledge which can be traced back to the late Middle Ages? How can this development be adequately described and how, on the basis of such a description, can the significance of this process for the early modern history of knowledge in the West be assessed? These are the overarching *questions* this book tries to answer.

There exists a considerable amount of literature concerning several stations and events in the course of this long development process as well as its various aspects,

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[31] For the debate about the Great Divergence, see, for instance, Pomeranz (2000) and Goldstone (2009).

[32] Among the economic and political conditions and factors that should additionally be taken into account for Europe's sustained development of natural and technological sciences, one factor deserves particular attention in my opinion, namely that industrial capitalism emerged as an economic system that compels every economic actor towards permanent innovations, forcing the state machineries to provide the necessary conditions for an adequate development of natural and technological sciences.

such as those indicated in our brief discussion of the economy of knowledge, that sustained this process. The majority of these studies focus on particular periods such as the Renaissance and particular countries like England or Italy, if not smaller localities; many of them try to locate stages of this process in an overarching cultural historical picture or dwell, particularly in recent times, on social issues such as the ambitions of practitioners who entered into commerce with educated persons or the latter's alleged or actual domination of the former.

As meritorious and indispensable as many of these studies are,[33] none of them tried to portray this process as a whole with its most essential branches. None of them made a wider comparison of the various ways in which learned and practical knowledge in the early modern age interacted in different areas of technological and scientific knowledge. What is more, many of them implicitly or explicitly took physics as a model of science, and thus highlighted mechanics and mechanical engineering as the model of all interrelations of practical and learned knowledge. By contrast, this book aims at a more complete portrait of the early modern interrelations and interactions between learned and practical knowledge. It tries to convey a new idea of the variety and disunity of these relations by discussing and comparing altogether six widely different fields of knowledge and practice.

The chosen fields are architecture, chemistry, gunnery, mechanical engineering, mining, and the various domains of practical mathematics including practical astronomy, mathematical geography and cartography, navigation, surveying and higher geodesy. Each of these fields of technologically advanced practice brought forth several kinds of technological literature which interacted in various ways with learned literature.[34] Needless to add that the chosen fields do not cover the whole spectrum of advanced practical knowledge of the early modern period; rather, they are thought to represent the *main types* of early modern technological knowledge.[35]

Mechanical engineering, to begin with, is the classic case of a field of advanced practice with a primary and well-defined counterpart in the world of learning – mechanics (statics, kinematics, and dynamics) – which had been inherited from

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[33] References to many items of this literature are given in the chapters below.

[34] It is not the goal of this book to provide a comprehensive history of each single field. In the case of mechanical engineering, for example, the goal is neither to present a history of early modern mechanical engineering nor a history of mechanics; rather, the book will trace the historical development of the technological and scientific literature pertaining to this field. As to the history of early modern theoretical mechanics and early modern mechanical engineering, there is hardly any demand for another account.

[35] Two important fields of practical knowledge – agriculture and medicine – will not be considered; the latter due to limits of competence, the former, although economically the most important production sector up to the eighteenth century, is omitted as it seems dubious whether it makes sense to trace learned elements of agricultural knowledge before the eighteenth century. As regards the practical knowledge of the crafts, this knowledge is, as mentioned above (note 6), involved only implicitly insofar as crafts were part and parcel of the specialized practical knowledge of one of the chosen technologically advanced fields of practice.