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Connecting the Scientific and Industrial Revolutions: The Role of Practical Mathematics

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Connecting the Scientific and Industrial Revolutions: The Role of Practical Mathematics.

Morgan Kelly and Cormac Ó Gráda*

Abstract

Disputes over whether the Scientific Revolution contributed to the Industrial Revolution begin with the common assumption that natural philosophers and artisans formed radically distinct groups. In reality, these groups merged together through a diverse group of applied mathematics teachers, textbook writers and instrument makers catering to a market of navigators, gunners and surveyors. From these "mathematical practitioners" emerged specialized instrument makers whose capabilities facilitated industrialization in two important ways. First, a large supply of instrument and watch makers provided Britain with a pool of versatile, mechanically skilled labour to build the increasingly complicated machinery of the late eighteenth century. Second, the less well known but equally revolutionary innovations in machine tools—which, contrary to the Habbakuk thesis, occurred largely in Britain during the 1820s and 1830s to mass produce interchangeable parts for iron textile machinery—drew on a technology of exact measurement developed for navigational and astronomical instruments.

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Introduction.

Although the Scientific and Industrial Revolutions stand as decisive transformations in western society, efforts to link the two run into an immediate difficulty.[1] How could the insights of a few hundred university educated natural philosophers corresponding with each other in Latin on topics in mathematics, physics and astronomy have been transmitted to industrial artisans and entrepreneurs whose educational level was often rudimentary at best?

The first response is to deny that any connection between the two revolutions existed or even mattered: see for example Clark (2012) and McCloskey (2011, 34). This scepticism is most systematically developed by Allen (2009, 238–271) who analyses the backgrounds of the major inventors of the Industrial Revolution and shows that most were "active, stirring, and laborious men" with few connections to Enlightenment learning. The second, taken by Mokyr (2011; 2016) and Jacob (1997), is to stress the diffusion of an Enlightenment culture of improvement and empiricism through popular science demonstrators, coffee shop lecturers, and scientific societies.

What neither side questions, however, is that *savants* and *fabricants* formed sharply distinct groups of people. In reality, however, natural philosophers and artisans merged together through a large and important, if often little known, group known to contemporaries as mathematical practitioners.

The radical economic and political changes experienced by sixteenth century Europe—changes driven by overseas trade and conquest, agricultural improvement, commercial expansion, and gunpowder warfare—drove a growing demand for trained navigators, gunners, surveyors, bookkeepers, military engineers, cartographers and others: all with skills in taking measurements and making calculations. In response there appeared teachers offering lessons in practical arithmetic and geometry; authors writing applied mathematics textbooks in the vernacular; and instrument makers producing tools for navigation, surveying, and other applications. Very often one person combined several of these activities.

These practitioners—applied mathematicians and instrument makers—made two central contributions to European, and in particular British, progress. First mathematics teachers caused useful numerical skills—such as decimals in arithmetic, logarithms in navigation, and triangulation in surveying—to diffuse rapidly

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[1] Naturally, the term Revolution is unhelpful in both cases, giving an impression of sudden events rather than centuries long processes: systematic advances in areas such as metallurgy were occurring by the seventeenth century (Broadberry et al., 2015); and 144 years separate Copernicus's *De Revolutionibus* from Newton's *Principia*.

into everyday use. Next, the widespread mechanical skill and precise measuring technologies that they created would eventually facilitate subsequent industrialization, first in advancing textile and steam machinery, and then in developing the machine tools needed to mass produce this machinery.

The technology of the late eighteenth century is often dismissed as having been fairly rudimentary (which raises the question of why it was not invented a good deal earlier). In fact, the two emblematic machines of early industrialization—Arkwright's spinning frame with its intricately meshing train of gears, spindles and rollers, and Watt's steam engine with it elaborate valve gear—were unusually complex technologies by the standards of the time. Much of Britain's success in developing these innovations from interesting concepts into successful industrial products rested on the expertise and versatility of its uniquely large pre-existing supply of ordinary instrument makers trained to make tools for navigation and surveying, as well as artisans in the closely related field of watchmaking.[2] Empirically Kelly, Mokyr and Ó Gráda (2020) find that much of the variation in industrial employment across the 41 counties of England in 1831 can be explained by their supply of mechanically skilled craftsmen in the late eighteenth century, and this in turn is correlated with the number of watch-making apprentices in the county in the mid-eighteenth century.

The second fundamental transformation of manufacturing occurred when precision measurement entered the workshop in the form of machine tools: machinery designed to cut and shape metal parts to an "almost mathematical exactitude and precision" in the words of the pioneering builder James Nasmyth (Musson, 1975). Contrary to the influential claims of H. J. Habakkuk (1962)—who made machine tools almost synonymous with the "American System of Manufactures" that arose in the 1840s—nearly every important type of machine tool was developed by British engineers in the period from 1820 to 1840, largely to allow the mass production of interchangeable parts for textile machinery. It is worth recalling the sheer size of the British cotton industry—where 150,000 power looms already lined factories in the late 1830s, and 300,000 a decade later—to appreciate the scale of the demand for precisely cut iron components, and to understand why Britain's machine tool industry was centred on Manchester.

Machine tools were indeed employed on a large scale in the United States for mass production in light manufacturing such as woodworking, hardware, and small arms. Habakkuk emphasized how much this machinery impressed Britain's leading engineer Joseph Whitworth on his visit in 1852, but neglected to add Whitworth's conclusion that compared with their own "engine tools", American tools

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[2] Throughout we use watchmaking as an abbreviation for watchmaking and clockmaking.

were “similar to those in use in England some years ago, being much lighter than those now in use, and turning out less work in consequence” and that the Americans “are not equal to us in the working of iron” (Musson, 1975).

Machine tools could be no more accurate than the measuring gauges and adjustment screws used to set them, but these vital components had been developing in astronomy since the sixteenth century. Between then and the early nineteenth century the accuracy of astronomical measurement steadily increased by a factor of 10,000 (the longest instance of rapid technological improvement in history: see Figure 2 below), and exactly cut angular scales and adjustment screws were already being incorporated into mass-produced navigational sextants by the 1790s.

Many of the advances in industrial technology during the late eighteenth and early nineteenth centuries ultimately came down to taking the gears, scales, and adjustment screws of mathematical instruments, clocks and watches (along with the lathes, gear cutters and other tools used to make them) and adapting them from the scale of brass instruments to that of iron machinery. The porous border between the worlds of precise scientific instruments and heavy industrial machinery is illustrated by the career of Whitworth who, after working on cutting the gears for Charles Babbage’s abortive Difference Engine, moved to Manchester to become the world’s leading producer of machine tools, and Britain’s foremost evangelist for standardized parts and precision manufacture.

Besides facilitating the development first of textile and steam machinery, and then of precision manufacturing and machine tools, mathematical instruments give useful insights into other aspects of early industrialization. These include the status of useful knowledge in different societies; the role of states and of guilds in advancing or retarding innovation; and the different evolution of manufacturing technology in Europe and China.

Looking first at the British culture of respect for useful knowledge and technical skill, leading instrument makers were commonly made Fellows of the Royal Society throughout the eighteenth century, but such honours for shopkeepers of humble origin who made a living with their hands were no novelty even then. The late seventeenth century clockmaker and son of a blacksmith Thomas Tompion, the “Father of English Watchmaking”, is buried beside the astronomical instrument maker and son of a small farmer George Graham in Westminster Abbey, something barely conceivable in France where, despite the strenuous support of Leibniz, the country’s foremost watchmaker Henry Sully was denied membership of the Royal Academy. Bertucci (2017, 83)

In the case of instrument making, the different fortunes of the English and French industries suggest that, in this one sector at least, guilds were inimical to technological progress (an issue addressed in general by Ogilvie, 2019, 438–510). Whereas the English trade was lightly regulated, French guilds were obliged to pay heavy taxes, a burden that turned them into repressive and mutually antagonistic entities that did not hesitate to enforce their rights to seize and destroy materials and tools, arrest non-members, and hinder the introduction of novel technologies. At a time when successful British instrument makers were establishing large workshops with extensive out-sourcing and division of labour, their French counterparts were limited to one apprentice at a time, so depriving the French economy of the abundance of mechanical skill that accelerated British industrialization: we will see below that although eighteenth century England had one third the population of France, it had at least three times as many instrument makers.

The development of practical mathematics and instrument making gives useful insights on the role of states in fostering innovation. Ordinary European seamen, just like their Chinese and Islamic counterparts, found simple navigational techniques to be adequate for their purposes. The expansionary states of Atlantic Europe generated a large market for trained navigators, gunners, cartographers, and surveyors; and directly supported efforts to advance the state of astronomy and navigation. The impetus to develop new instruments and to teach the mathematics needed to use them came from governments and state chartered trading companies, beginning in Portugal and Spain, and later in England and the Netherlands.

Finally, the divergent attitudes to applied mathematics between Europe and China is revealing. Although periodic government efforts to discourage overseas trade had less impact than sometimes claimed, the Chinese state never gave any support to improve navigational science of the sort given in Europe. At the same time, the view that the legitimacy of the state rested on the Mandate of Heaven made astronomy a politically fraught and tightly controlled activity. Chinese astronomy and navigational science stagnated in consequence, and no large industry of skilled instrument makers ever emerged.

In terms of the existing literature on the origins of the Industrial Revolution our goal is to reconcile the contribution of ordinary artisan skill emphasized by Allen (2009) and Kelly, Mokyr and Ó Gráda (2020) to the studies of Mokyr (2011; 2016) and Jacob (1997) that emphasize the diffusion of Enlightenment culture of improvement and empiricism. We describe an additional conduit for the dissemination of useful knowledge both upwards and downwards, as well as the role of European states committed to improving the level of navigational and astronomical knowledge and technology; and the respect of elite natural philosophers (at least in Britain) for the artisan virtues of mechanical expertise. The term artisan virtue deliberately echoes the complementary bourgeois virtues of thrift, diligence, and respectability whose importance has been highlighted by McCloskey (2006).

Musson and Robinson (1969, 427–458) first showed the importance of a large supply of instrument makers and watchmakers for the development of cotton spinning in the late eighteenth century. However, the revolutionary development of machine tools in Britain in the 1820s and 1830s has received little attention in economic history outside the neglected study of Musson (1975).

The study of early English applied mathematicians and instrument makers was pioneered by Taylor (1954). The role of ordinary artisans of the late sixteenth century with their culture of empirical experiment, use of geometry, and disdain for academic authority as sources of the Scientific Revolution was first argued by Zilsel (1941; 1942) and Rossi (1970) (and has been noted in the economic history literature by Mokyr (2016, 136–138)); and more recently by Bennett (1986) among others: see Cormack (2017) for a recent overview.

1 Mathematical Practitioners and Instrument Makers

The economic and political transformation of Europe in the sixteenth and seventeenth centuries—with gunpowder warfare, maritime trade, territorial expansion, land enclosure and agricultural intensification—created a substantial market for practical expertise in navigation, surveying, gunnery, cartography and other fields, an expertise which usually came down to being able to use instruments to measure angles, and then to make calculations with these numbers. To provide the necessary training there appeared a large group of individuals of varying backgrounds making their living as applied mathematicians, teachers, and instrument makers: the so-called mathematical practitioners. While some practitioners offered lessons in subjects ranging from commercial arithmetic and book-keeping to navigational trigonometry and logarithms, others published textbooks in the vernacular that often included lengthy sections explaining how to use the relevant instruments, as well as where they could be purchased. Some teachers and authors moreover designed, and sometimes also made and sold, instruments for measurement and calculation. Notable early centres of such mathematical practice were Augsburg with its tradition of exact metal work and engraving, the large port of Antwerp and nearby Louvain, and, from the late sixteenth century, London.

We should introduce some terminology. Before the nineteenth century the word Science in its modern usage did not exist, being known instead as Natural

Philosophy, nor, by extension, did the term scientific instrument.[3] There were instead three sorts of instrument: philosophical (air pumps, barometers, electric machines), optical (telescopes and microscopes), and, our concern here, mathematical. Mathematical instruments were designed to measure angles for applications in astronomy, navigation, surveying and so on (alongside calculation instruments like slide rules), and we will usually refer to them, as most contemporaries did, simply as instruments.

During the sixteenth and early seventeenth centuries simple, practical instruments advanced rapidly. For navigators there appeared astrolabes, backstaffs, variational compasses, and nocturnals (for telling time at night); while surveyors replaced ropes and poles with theodolites, sighting compasses, plane tables and measuring chains; and adopted the technique of measuring distance by triangulation, devised by the mathematician Gemma Frisius in 1533. The new calculating instruments of the early seventeenth century included Napier's Bones for arithmetic, and Gunter's Rule for navigational trigonometry.

After Napier conceived the idea of logarithms in 1617, within months they had been turned into fairly accurate tables in their familiar base 10 form by Henry Briggs, the Professor of Mathematics at Gresham College in London. His colleague Edmund Gunter incorporated these for his Rule which had trigonometric values marked on one side and their logarithms on the other, so that navigators could carry out calculations simply by adding or subtracting lengths stepped out with a divider (it was still used by the Royal Navy until the 1840s). Another important transfer from mathematical theory to everyday calculation was the replacement of fractions with decimals, advocated by Simon Stevin among others and applied notably in Gunter's Chain (a standard surveying tool until the mid-twentieth century) where each yard, indicated by a brass link, was separated with 9 iron links.

The Lutheran Reformation drove a rapid growth of one mathematically based form of useful knowledge to which Catholicism was increasingly antagonistic: astrology (Westman 2011, 141–170; Barnes 2016, 139–171). Apart from the usually illegal activity of forecasting political events such as the overthrow of kings; astrology gave farmers weather forecasts, and allowed doctors to choose the appropriate treatment for individual patients: early mathematicians such as Girolamo Cardono were commonly also physicians. The advances of Tycho Brahe and Johannes Kepler were motivated in part by their active careers as astrologers; and the central

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[3] *Scientia* typically referred to certain knowledge, such as geometry a distinction captured in John Locke's conclusion "that natural philosophy is not capable of being a science" (Harrison, 2007, 223). However the fusion of what are now called astrology and astronomy was known as "the science of the stars" *scientia stellarum* Westman (2011, 30).

role of mathematics in Philip Melanchthon's fundamental reforms at the University of Wittenberg, that were the foundation for Lutheran Germany's unmatched university system, stemmed from a perceived need to improve the level of astrological practice. Rutkin (2006, 553) sees the Jesuit counter-attack, driven by Europe's leading author of advanced mathematics textbooks Peter Clavius, as an important factor driving astronomy to separate from astrology.

For many in England mathematics continued to be "smutted with the Black Arts" of astrology (some parents supposedly forbade their sons to attend Oxford after it established its first Professorship of Geometry in 1619: Taylor 1954, 4). In reaction, the first English practitioners were at pains to stress the practical usefulness of their subject, both to individuals and the state (Neal, 1999), while at the same time disparaging the learning of university scholars "beeying in their studies amongest their bookes" in favour of the sort of knowledge earned by practical experience and "exact triall and perfect experimentes" (Bennett, 1986).[4]

Among these practitioners, supposed boundaries between desks and workbenches, hand work and brain work, knowledge and know-how, become so blurred as no longer to be useful: in the words of the mathematician-astrologer John Dee "A speculative Mechanicien…differeth nothynge from a Mechanicall Mathematicien" (Bennett, 2006). Instead, the practitioners of the sixteenth and seventeenth centuries spanned a continuous spectrum that ranged from anonymous artisans and schoolmasters to figures now usually classified as scientists and mathematicians, but whom their contemporaries saw equally as teachers, instrument makers, and engineers. Such practitioners include Georg Rheticus, Johannes Stoefler, Jost Burgi, Johannes Regiomintanus, Peter Apian, Gemma Frisius, Gerard Mercator and, most notably, Simon Stevin and Galileo Galilei.

Besides making fundamental contributions to hydrostatics, mechanics, mathematics and astronomy, Stevin was employed as quartermaster to the Netherlands army, and published on practical topics including book-keeping, fortification, applied navigation, and drainage, alongside popularizing the use of decimals (Dijksterhuis, 1970). Galileo, as Valleriani's (2010) pioneering study *Galileo Engineer*

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[4] This emphasis on empirical observation and mathematical analysis coupled with a scepticism towards received dogma, are, of course, some of the hallmarks of the new natural philosophy that gradually appeared in the seventeenth century. A long-standing question, dating back to Zilsel (1941; 1942), has been how much the new science owed to mathematical practitioners (what Zilsel termed "superior artisans"). Zilsel's view that the overthrow of the sterile scholastic and humanistic pursuits of the universities owed a good deal to mathematical practitioners was developed subsequently by Bennett (1986), as well as Rossi (1970, 63–99) who argued that a direct path from these practitioners with their concern for useful knowledge ran through the writings of Francis Bacon and thence into the Enlightenment: for an overview see Cormack (2017).

describes, for much of his life earned a considerable share of his income teaching military engineering and manufacturing instruments: first a “geometric and military compass” for performing calculations and setting the elevation of artillery, and then optical instruments. Much of Galileo’s theoretical work, moreover, was informed by his practical activities, notably his theory of the strength of beams that grew out of earlier consultancy on the performance of Venetian galleys.[5] Indeed there is very little in the biographies of iconic eighteenth century engineers like Watt or Smeaton—at first supporting themselves by making and selling scientific instruments and surveying canals and harbours, followed by increasing fame as inventors and engineers—that would have seemed unusual in the early seventeenth century.

The daily activities of Robert Hooke described by Iliffe (1995) show the absence of clear boundaries between study and workshop as he moved between gentlemen natural philosophers, instrument makers, and artisans. After being shown the calculating machine that had taken Leibniz several years to construct, Hooke was supposedly able to draw on this circle to make a copy within weeks (Jones, 2016, 64). Even as mathematical practice had begun to separate between artisans and academics in the late seventeenth century, leading mathematicians had not lost sight of practical utility: for Isaac Newton (2008, 291) geometry “was devised, not for the purposes of bare speculation, but for workaday use” which meant that its techniques should be such that “any practitioner should find them readily applicable in his measuring.”

1.1 Applied Mathematics Texts

An idea of the growth of mathematical practice in Britain at this time can be derived from the number of mathematics books published in English (as opposed to the Latin used by scholars in communicating with each other). These textbooks were largely aimed at a broad market unlike the elaborately illustrated Books of Machines of Agricola, Biringuccio and others discussed by Rossi (1970, 42–62).

Figure 1 gives the number of applied mathematics books published each decade between the 1520s and the 1740s taken from titles that are listed in the British Library *English Short Title Catalogue*[6] under the subject headings arithmetic (460), astronomical instruments (49), bookkeeping (108), compasses (30), geometry (186),

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[5] *Two New Sciences* opens with a conversation in the Venetian Arsenal, then the world’s largest industrial enterprise and a pioneer in the use of standardized, interchangeable parts to allow large fleets of war galleys to be assembled at short notice (Lane, 1934, 146–175).

[6] `http://estc.bl.uk`.

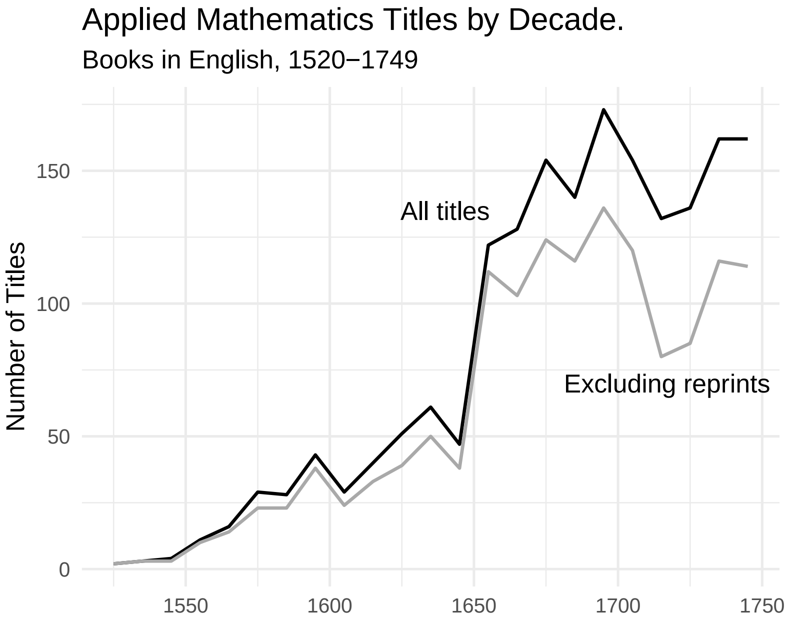

Figure 1: Number of titles in applied mathematics published in English by decade, 1520–1749.

gunnery (58), logarithms (99), mathematics (407), mathematical instruments (93), measuring (155), navigation (538 excluding government publications), shipbuilding (57), surveying (126), and trigonometry (100). After eliminating double counting of books listed in several categories this gave 1,827 titles, and 1,406 when reprinted editions are removed. As Figure 1 indicates, the number of books on applied mathematics published rose sharply and almost continually, from hardly any in the mid-sixteenth century to over 100 new titles per decade a century later, not counting reprints of titles that had proven popular.

To put the rapid growth of these titles into perspective, Buringh and van Zanden (2009, Table 2) estimate the the number of books printed in England grew about thirty-fold between the early 1500s and the late 1600s. It is notable that they too find a stagnation of output in the early eighteenth century,

1.2 Astronomical Instruments

By the mid-seventeenth century most of the necessary mathematics for surveying and navigation (plane and spherical trigonometry, and logarithms) had been formulated, as had the instruments in everyday use. Subsequent innovations in instrument design were driven in large part by the demands of state funded observatories.

At the pinnacle of instrument making stood astronomical instruments and the makers who designed and built them. Unlike modern astronomy (and that of Imperial China) which is concerned with observing interesting celestial objects, until the mid-nineteenth century western astronomy (like its Hellenistic and Islamic ancestors) was mostly about tracking the paths of stars and planets across the sky for the purposes of making star maps.[7] This meant recording the precise time and angle at which each star or planet crossed the observatory's meridian (south facing line). Along with exact pendulum clocks, this called for large quadrants that had sighting telescopes with cross-hairs and micrometer eyepieces, exactly made angular scales with verniers read through microscopes, and perfectly cut adjustment screws. The development of astronomical instruments is in large measure the history of increasingly accurate technology for dividing scales, as the titles of Bennett's (1987) and Chapman's (1990) standard histories—*The Divided Circle* and *Dividing the Circle* respectively—suggest.

Figure 2 shows the steady rise in the accuracy of observatory clocks and the resolving power of observational instruments from the middle ages until the early nineteenth century: in both cases instruments were 100,000 times more accurate than they had been 350 years earlier.[8] These steady advances in accuracy, of five orders of magnitude or 3.5 per cent per year, probably mark the longest sustained episodes of rapid technological progress in history and directly contradict the widespread view that, barring isolated spurts, technological stasis was the norm before the late eighteenth century.[9]

Of vital importance for the subsequent evolution of precision manufacturing were accurately cut adjustment screws, developed originally to move the image of a star exactly into the cross-hairs of a telescope. This technology was first transferred from large and expensive observatory equipment to everyday instruments by the leading instrument builder of the late eighteenth century, Jesse Ramsden.

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[7] Since at least Aristotle, most attention focused on understanding the movement of the perfect and immutable heavenly spheres, rather than the changeable and chaotic world below the sphere of the moon, which the comets and novae which preoccupied Chinese astronomers were believed to inhabit.

[8] Information on time-keeping is from Pledge (1939, 70) supplemented by the estimate for Burgi's clock from Roche (1998, 58). The accuracy of angular measurement comes from Chapman (1983).

[9] The nearest comparable rise is Hoffman's (2011, Table 1) estimate that the productivity of French cannon manufacture rose by 0.6 per cent per year from 1463 to 1785: a sevenfold increase.

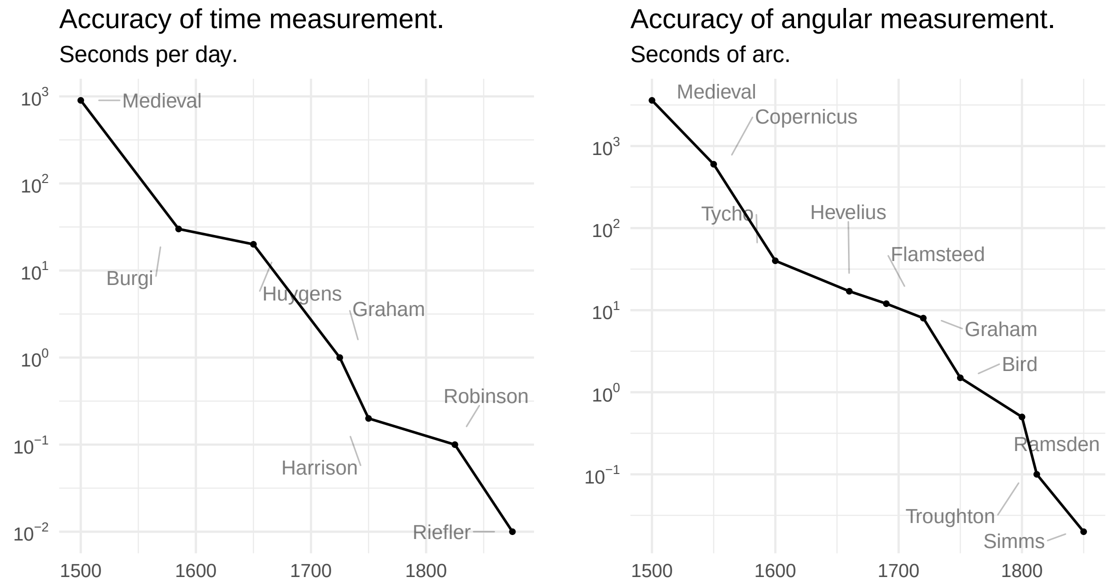

Figure 2: Accuracy of time and angular measurement from medieval times until the early nineteenth century.

He succeeded in cutting adjustment screws of unprecedented exactness that could then be used as templates in his Dividing Engine to mass produce the scales of sextants. In place of laborious and inexact engraving of scales by hand, each turn of the screw made an exactly spaced division. This fundamental combination of adjustment screws and exact measuring scales was then available for the precision manufacturing of interchangeable machine parts, especially for textile manufacture, that emerged in Britain in the 1820s.

2 Instrument Makers and Industrialization.

So far we have highlighted two of the contributions of practical mathematics to European development between the sixteenth centuries. First there was the spread of mathematical techniques ranging from arithmetic using Arabic numerals and decimals to trigonometry and logarithms, all part of a culture of exact quantification that intertwined with the growth of increasingly commercialized societies.[10] Then we saw how the development of instruments such as theodolites, quadrants, and sighting compasses contributed to the technology of economically important activities, in particular navigation and surveying.

However, a third contribution came in the way that instrument making brought into being a substantial range of capabilities in both skills and technology, capabilities that facilitated early industrialization in two ways. At the everyday end of commercial instruments was a large labour force of mechanically skilled artisans making navigational and surveying instruments and watches, as well as the lathes, files, and gear-cutting machines needed to make the necessary parts. The skills of these anonymous artisans were at a premium when it came to building the increasingly complex cotton machinery and steam engines of the late eighteenth century. The second advance, between 1820 and 1840, was the less well known but equally important Machine Tool Revolution. Driven by the need to mass produce interchangeable parts for increasing amounts of iron textile machinery, British engineers developed heavy but exact metal cutting machinery, a process facilitated by having extremely precise measuring scales and adjustment screws already developed for scientific astronomy.

2.1 The Early Industrial Revolution.

The fact that two of the best known early mechanical innovations—Hargreave's spinning jenny and Newcomen's atmospheric engine—were fairly simple artefacts has contributed to a widespread misconception that the machinery of the early Industrial Revolution was technologically rudimentary. In fact the next generation of machinery—Arkwright's water frame with its intricately meshing rollers, spindles and gears , and Watt's engine with a sophisticated valve chest—were complicated technology by the standards of the time.

The way that an abundance of watch-making skill in north-western England expedited the development of the Manchester cotton industry was highlighted by Musson and Robinson (1969, 427–458). The fact that the first important textile innovation, the spinning jenny, was a simple artefact has led to the widespread misconception that the cotton machinery of the early Industrial Revolution was technologically primitive. However as the leading Manchester cotton spinner John Kennedy recalled in 1815, with the appearance of Arkwright's water frame and its

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[10] However, as Cohen (1999, 23–24) notes, in a world where goods and money were measured in non-decimal units, practical numeracy was not a straightforward accomplishment, leading to the widespread use of commercial ready reckoners.

intricately meshing metal rollers, spindles, and gearing "a higher class of mechanics such as watch and clock-makers, white-smiths, and mathematical instrument makers began to be wanted; and in a short time a wide field was opened for the application of their more accurate and scientific mechanism." This demand can be seen in the abundance of contemporary newspaper advertisements looking for these skills Musson and Robinson (1969, 436).

In 1791, the engineer John Rennie in London was complaining that because of its high wages "in respect to workmen, the Cotton Trade has deprived this place of many of the best Clock Makers and Instrument Makers so much so that they can scarcely be had to do the ordinary business." Even in 1825, the London engineer John Martineau could claim that his first response to a rise in demand would be to hire craftsmen from the watch- and instrument-making trades because "with a very little practice" they could perform "a great deal of work" in an engineering factory (Woolrich, 2002, 40).

For early Boulton and Watt engines, apart from the cylinder nearly all of the other components, notably the boiler, had to be supplied by the customer. However, one component was always produced in their Soho works, and that was the complex valve chest that controlled the flow of steam through the parts of the engine, and that was a part that could be produced easily given a large supply on instrument- and watch-makers.

2.2 The British Machine Tool Revolution, 1820–1840.

When it came to working brass for watches and other instrument parts, a substantial range of cutting tools had evolved by the late eighteenth century including lathes, gear cutters, and files: the catalogue of John Wyke of Liverpool ([1797] 1977) had 62 illustrated pages of tools including, on its first plate, 45 different types of file. Iron parts for machines, by contrast, had to be laboriously chipped into shape using a hammer and chisel and, if necessary, finished off with a file: techniques that had hardly changed since the middle ages. This process was not only expensive and time-consuming but resulted in irregular parts so that early machinery was built where possible out of wood (including the beam and most of the frame of early Watt engines; and the drive shafts and gearing used to connect machinery with power sources in factories) or, like the gearing of early textile machinery, of rapidly wearing brass. In effect machine tools represented the scaling up of precision metal cutting instruments from the shaping of brass to the cutting of the iron components needed for the rapidly increasing numbers of ever larger and more powerful machinery.

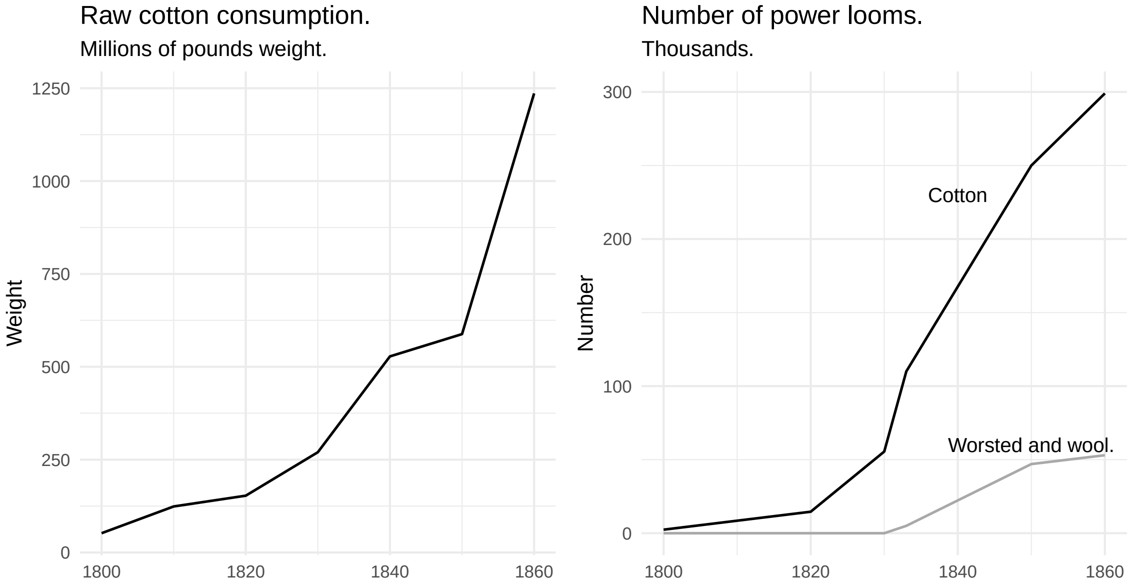

Figure 3: UK consumption of raw cotton and number of power looms, 1800–1860.

Habakkuk (1962) made much of Britain's supposed failure to develop mass production using interchangeable parts, in comparison with the "American System of Manufactures" that developed after 1840.[11] Whereas Britain, Habakkuk claimed, could avail of abundant supplies of skilled craftsmen, America was forced to substitute self-acting tools operated by unskilled workers in their place. Habakkuk's argument is both widely cited and, as demonstrated by Musson (1975, 128–135), historically inaccurate: every major machine tool in use in the mid-twentieth century was developed in Britain, largely in the period 1820–1840, to mass produce interchangeable parts for iron textile machinery and then, in the early 1850s, to replace skilled engineering workers with cheaper labourers.

The implausibility of the Habakkuk thesis is demonstrated in Figure 3 which illustrates the rapid expansion of textile production in the first half of the nineteenth century. The consumption of raw cotton in 1850 was over ten times what it had been in 1800 and this was matched from the 1820s by the growth in power looms. There were already 150,000 cotton looms in the late 1830s, and this had

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[11] Similarly Rothbarth (1946) and Rosenberg (1969) claimed that nineteenth century Britain had never developed mass production, whereas Temin (1966) cautioned against the narrow focus on revolvers, woodworking, and hardware taken by Habakkuk.

risen to a quarter of a million by 1850, with another 50,000 looms in worsted and wool. Supplying these looms in 1856 were 28 million spindles in cotton, and 3 million in worsted and wool, all driven by 140 million horsepower of steam (Bigelow 1862, Tables 104, 108; Cookson 2018, Table 8.3). This expansion is matched by the growth in official machinery exports from £0.2 million in 1825, to £1.1 million in 1846, £2.2 million in 1855, and £3.7 million in 1859: nearly 8 per cent of the value of cotton exports (Bigelow 1862, Table 94).[12]

These large numbers of textile and steam machinery, made from fairly rapidly wearing iron, created a large market for mass produced, interchangeable components needed both for machined iron frames and for a continual stream of replacement gears and other moving parts, all relying on "the exactitude and accuracy of our machine tools. . . which the unaided hand could never accomplish."[13] There was no way that Habakkuk's skilled British craftsmen, however cheap and abundant, could produce exact parts for the hundreds of thousands of uniform machines that lined early-Victorian textile mills without the aid of heavy iron cutting machinery: particularly lathes, planers, and gear cutters. These machine tools were developed, first in London and then in Manchester, by Henry Maudslay and the circle of men who had spent more or less time in his workshop that included Joseph Clement, James Fox, Richard Roberts and Joseph Whitworth; as well as the Swiss-born John George Bodmer.[14]

Of these the most notable is Roberts who in 1822 patented the first commercially successful power loom, before patenting the self acting mule in 1830. As well as being a leading locomotive manufacture and pioneering the large scale use of standardized templates and gauges, among machine tools Roberts developed some of the first effective gear cutting and planing machines (both vital for mass-producing machinery) besides improved lathes, drills, and slotting machines. In terms of labour saving, to produce a large, flat metal part by hand chipping and filing cost 12 shillings a square foot, whereas with a planing machine it cost one penny (Hills, 2002, 63–113, 127–155).

In contrast, then, to the American mass production of consumer goods—furniture, hardware, and small arms—that preoccupied Habakkuk and Rosenberg, the British industry specialized in machine tools for heavy engineering, and retained its tech-

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[12] The export of some types of machinery began to be legalized in 1825, but that of modern machinery was banned until 1843: Clapham (1951, 484–485).

[13] William Fairbairn, cited by Smiles (1864, 361). Another notable example where machine tools were used extensively to manufacture interchangeable parts was in Donkin's production of Foudrinier's paper-making machinery: Musson (1975, 111).

[14] Standard histories of early machine tools are Roe (1916), Rolt (1965) and Woodbury (1972).

nological leadership until perhaps the 1890s (Floud, 1974). Precision apart, and again contrary to Habakkuk's notion of cheap craftsmen, British manufacturers were increasingly motivated to adopt machine tools through a desire to replace skilled metalworkers—who, besides insisting on seven year apprenticeships, were perceived as overpaid and strike prone—with cheaper and more tractable labourers.

This process culminated in the successful 1852 Lock-Out of engineering workers by major employers (Burgess, 1969), an event that in some ways marks the end of artisan mechanical skill as a driver of British industrial development. The growing availability of self-acting machine tools meant moreover that shortages of mechanical skill became less of a disadvantage for European economies, which can be seen for instance in the rapid appearance of locomotive building in France and Germany.

2.3 From Mathematical Instruments to Machine Tools.

Maudslay began his engineering career in 1789 working for Joseph Bramah (inventor of the hydraulic press) to develop machinery to mass produce the intricate parts for the padlock that Bramah had designed, and to do this he devised a range of cutters that were adjusted with micrometer screws. Accurate machine tools required two things that Maudslay went on to pioneer: gauges to produce perfectly flat guiding surfaces; and exactly cut machine screws for setting and adjusting moveable parts. For instrument making, Ramsden had produced an exact screw cutting lathe in 1777 whose all metal construction and precision closely anticipate Maudslay's, leading Daumas (1958, 388) to suggest that, given Ramsden's fame and the fact that details of his lathe were published, Maudslay may have been influenced by Ramsden's design. One of Maudslay's most noted displays of virtuosity in later life was cutting a five foot long adjustment screw threaded to 50 turns per inch for calibrating instruments in the Royal Observatory, receiving a £1,000 prize for the achievement (Rolt, 1965, 89).

Habakkuk (1962, 120) dismissed the automated production of naval pulley-blocks by Brunel and Bentham as a dead end in British manufacturing "with little or no influence on the general manufacturing of the country." It is notable that this machinery was built by the young Maudslay, whose name is absent from Habakkuk.

Maudslay's successor as the evangelist of precision manufacturing and interchangeable parts was Whitworth who, early in his career, worked for Clement cutting the brass gears for Charles Babbage's Difference Engine. This task needed "a special aptitude for the minute accuracy of detail in mechanical work [that] … Mr Whitworth in after life certainly made the most of." The role of Babbage's project in stimulating the development of precision industrial tools was acknowledged by leading contemporary engineers such as Fairbairn and Nasymth, and was summarized in 1855 by the President of the Royal Society: "This Country has received an equivalent many times over for the expenditure on the Calculating Engine, in the improvements in tools and machinery directly traceable to the attempt to make it" (Jones, 2016, 206).

Following the collapse of Babbage's project, Whitworth returned to Manchester in 1833 to set up his own engineering business. For his employees at the time working to a sixteenth of an inch was seen as "something like perfection in mechanical finish" but by the 1850s Whitworth's "self-acting machines are made, adjusted, and fitted to the ten thousandth of an inch" using the standard gauges for which he became famous (Hyman, 1982, 231). This transfer into machine building of an exactitude previously associated with astronomy is encapsulated by the way that in 1775 Boulton could admire how Wilkinson's boring of their steam cylinder "doth not err the thickness of an old shilling in no part", whereas thirty years later Maudslay's "Lord Chancellor" micrometer was accurate to 0.001 inches (Roe, 1916, 45), and at the 1851 Great Exhibition Whitworth displayed a micrometer accurate to one millionth of an inch used to set his factory's measuring gauges (Musson, 1975).

Turning from instruments to theory, a direct connection from mathematics to machinery runs through the question of how to design gearwheels to transmit power with minimal friction and wear. The first mathematicians to lay down the systematic geometrical principles of gear design—showing that teeth should have a cycloid profile—were de Philippe de la Hire in the 1690s and Charles Camus in 1733, and design of gear teeth to minimize friction was analysed comprehensively by Leonhard Euler in the 1750s. In terms of industrial applications by elite engineers, Robert Willis in 1838 designed a ruler for measuring out gear profiles, and Whitworth's cutters from the late 1830s could cut properly shaped teeth; but the first instructions aimed at ordinary shop workers originated with Rennie in his 1841 revision of Buchanan's popular *Treatise on Mills and Millwork* (Woodbury, 1972, 9–31, 62–74).

3 England versus France: Guilds and Industrial Organization.

By the time that Adam Smith decried an “altogether unnecessary” guild system that restricted competition and took year to impart artisanal skills that required no “long course of instruction”, guilds in England were far from being the institutional encumbrance he claimed them to be. Minns and Wallis (2012) demonstrated that many apprentices left before their full term; and in many trades, including watchmaking as we will see below, ordinary artisans were often not indentured.

3.1 English Guilds and Industrial Organization

From at least the mid-seventeenth century, enforcement of guild restrictions in London was lax and legal actions against members uncommon: in the Clockmakers’ Company the last fine for “Insufficient Quality” recorded in Atkins and Overall (1881, 235–240) took place in 1688. As Stewart (2005) observes, Livery Companies came to conduct their affairs in a stylized way that had more to do with publicizing their high standards of workmanship than policing members, with “searches” or “walks” purportedly to examine workshops for low quality products conducted in official costume at pre-announced times.

The Clockmakers’ Company explicitly surrendered its right of search in 1735 as "interfering with the liberty of the trade" and was followed in this by other guilds. By 1753 a committee of the House of Commons, articulating growing concerns that guilds were inimical to the rights of private property, concluded that searches were "injurious and vexations to manufactures, discouraging to industry and trade, and contrary to the liberty of the subject" (Stewart, 2005).[15]

Instrument makers were indeed obliged to belong to some guild but because there was no specific guild for their trade, by the “custom of London” they were free to join whatever one they pleased including the Grocers, the Drapers, and many others besides the Clockmakers (Brown 1979; Crawforth 1987, Ogilvie 2019, 499). This relaxed attitude of guilds facilitated the rapid growth of out-sourcing and specialization in the watch- and instrument-making industries. As McConnell (1994) shows, there was by 1750 an established hierarchy of instrument firms. At

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[15] At the same time, requirements that apprentices serve a seven year term continued to be enforced by the trade clubs of skilled journeymen (which often operated in the guise of friendly societies to evade legal prohibitions on combinations of workers, and were in many ways the successors of guilds) that evolved into trade unions, starting with the Amalgamated Society of Engineers in 1851 (Chaloner, 1969).

its peak were elite astronomical makers, such as Jesse Ramsden, running large workshops and supplied by an extensive web of subcontractors; and below them were reputable specialists serving larger, commercial markets, especially in navigation and surveying. These were followed by the subcontractors making parts for firms above them; and, finally, at the bottom were low quality makers producing cheap instruments such as thermometers and hydrometers for brewers.[16] The overall result was a flexible structure able to respond swiftly to changes in market demand: see Riello (2008) and Ben Zeev, Mokyr and van der Beek (2017).

3.2 French Guilds

Adam Smith's strictures against guilds were more applicable to *ancien régime* France, yet even there, as a literature dating back to Fauché (1913) demonstrates, the power of guilds to control employment and output varied considerably across trades, and in many cases was considerably weaker on the eve of the Revolution than a century earlier. In many cities outside Paris guilds were effectively powerless, and large scale production beyond guild control took place in the Paris faubourgs (suburbs) of Saint Antoine and Saint Marcel: for an overview see Ó Gráda (2018).

However, the guilds that controlled French instrument making were extremely litigious organizations, making full use of their rights to search workshops; seize or destroy tools, products and materials; and to arrest and fine offenders. These powers were not only deployed against craftsmen who were not affiliated to any guild but to harry members of rival guilds as described by Daumas (1972, 93–98).[17]

The supply of instrument makers was tightly restricted by the requirement that each journeyman had to produce a masterpiece and pay a large entry fee (500 livres in the case of the Founders) on top of heavy annual dues. Moreover, in contrast to the large workshops run by successful London makers, each master was limited to training, besides his sons, one apprentice at a time. This meant that over his working life a master, no matter how talented, might train only three or four apprentices, in contrast to the dozens who passed through elite London workshops like Ramsden's.

The case of France's leading instrument maker Etienne Lenoir is instructive. In 1785 while making instruments for the Royal Observatory—under a police guar-

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[16] The central role of these simple instruments in enabling a large scale brewing industry to emerge was highlighted by Mathias (1959, 63–78): see also Nuvolari and Sumner (2013).

[17] A revisionist account of how guilds diffused innovations in horology and instrument making is given by Turner (2008). However, in contrast to its lengthy treatment of England, the discussion of France is less detailed and omits any reference to the standard account of Daumas.

antee that, as the only person in France capable of this undertaking, he would not be harassed by guilds—he was arrested by the Founders' Guild (an organization dominated by makers of cannons and bells to which instrument makers had to belong). They confiscated his materials and brought him before a magistrate. The magistrate, although sympathetic to Lenoir, fined him 36 livres to cover the cost of the confiscation, and counselled him to join the Founders because there existed no legal protection against the actions of a guild sanctioned to seize anyone working without its permission.

A major advance in making watches and instruments came with the rolling of brass into thin sheets, which allowed parts to be made to an exact thickness. Although this appeared in England in the mid-seventeenth century (Kelly and Ó Gráda, 2016), the opposition of the Plumbers' guild ensured that it was only allowed in France in 1786.

In terms of their industrial organization, unlike the almost factory scale production of their English counterparts, French instrument makers (just like their watchmakers) catered largely to a luxury market of the royal court, universities and the Academy leading to small scale enterprises that lacked both the working capital and the skilled labour needed to produce large astronomical instruments. As a result, although English science in the eighteenth century was largely eclipsed by its French counterpart, the French still relied on London makers to provide instruments for their most ambitious projects.

4 The Supply of Precision Mechanical Skill.

The success of the English instrument industry relative to its French counterpart is indicated in Figure 4. This shows the number of known instrument makers by decade for both countries from the 1500s to the 1810s, taken from the Webster Signatures Database.[18] We divide makers into mathematical (including surveying and navigational), and all others: either makers of optical or philosophical instruments, or those on whom no information is available beyond their names. For most early makers the only date known is when they were active (flourished), and in those cases we assign them a date in the middle of their careers. When their date of birth is recorded, we assign makers to the decade when they were 30 years old.

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[18] `http://historydb.adlerplanetarium.org/signatures/all.pl`. The data are based on several national listings of instruments, supplemented with information from a large number of museums compiled by the Websters.

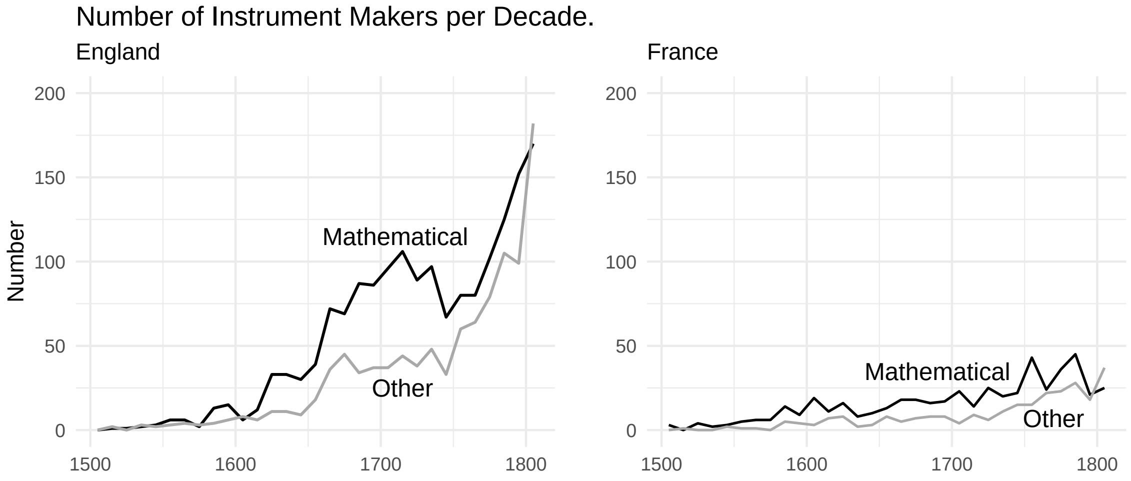

Figure 4: Known English and French makers of mathematical and other instruments.

In other words, the diagram gives a measure of the flow into the industry rather than the stock of all makers active at any time.

That the French industry was small and relatively stagnant relative to England's is immediately apparent, but it is likely that Figure 4 understates the true difference. The Webster data are mostly based on museum pieces which tend to be expensive instruments. As we noted, the French industry was geared towards prestigious markets and a greater share of its output has probably survived than the utilitarian navigational and surveying instruments produced in large quantities in England, instruments which would often have been used until worn out and then discarded. For instance, of 2,711 English entries only 94 makers of surveying instruments are recorded.

A second reason why the relative scale of England's industry may be understated in Figure 4 stems from differences in the organization of the two industries. French makers were invariably small operations whereas many described in England as instrument makers, just like their watchmaker counterparts, were company owners who put their signature on a finished item assembled in their workshops from parts made by anonymous employees or sub-contractors.

Given the inevitable selection biases in surviving scientific instruments, a useful complementary indicator of the supply of precision mechanical skill is the number of watch- and clock-makers. This can be gauged from the records of the London Clockmaker's Company where details of every apprentice between 1700 and 1810 were compiled by Moore (2003). Between the early and late eighteenth century the annual number of apprentices doubled from around 100 to 200 per year.

An inevitable limitation of this measure is that many watchmakers may have served no formal apprenticeship. We can, however, gauge the extent of this undercounting in two ways. The first is to use the 1851 census which lists the number of watch- and clock-makers aged 60–64: men who would have been born in the years before 1790 and apprenticed in the early 1800s. There are around 120–150 of these men by year of age. Assuming that fifty per cent of men in the early nineteenth century survived from their late teens into their early sixties (which is what Haines (1998) estimated for white American males in 1850), we have somewhere around 2,400–3,000 apprentices trained in the decade around 1800, roughly twice the number registered with the Clockmakers' Company. For comparison, there were 298 instrument makers in their sixties (roughly the same as we would expect from Figure 4), and 214 in their fifties.

We can estimate the exact share of watchmakers who had been formally apprenticed in one important centre for making parts and tools: Prescot outside Liverpool. Unusually, Prescot's marriage registers record the occupation of the groom, allowing us to check whether each man described as a watchmaker was ever formally apprenticed to the guild. It turns out that for the eighteenth century only 21 per cent (56 out of 269) of these watchmakers appear in Company records. This is well below the fifty per cent nationally and probably reflects the low value-added activities conducted there.

5 The Role of the State.

Most of the demand for innovation did not come from the private sector. By encouraging innovation and generating demand, European states actively promoted the development not only of utilitarian tools for navigation, gunnery, and surveying but of expensive observatory instruments for astronomy. Innovation was encouraged further by governments through patents and prizes. However, an early impetus to mathematical practice came from princely courts in the fragmented states of Italy and Germany. In Italy machine design, fortification, public buildings, and hydraulic projects (building canals, aqueducts, and draining land) engaged architect-engineers like Brunelleschi, Leonardo, and Taccola (Bennett, 2006), while in Germany, where several princes were notable astronomers, an additional concern was improving state mines (Moran, 1981).[19]

5.1 Navigational and Surveying Instruments.

Until the late fifteenth century, European sailors mostly engaged in coastal navigation, guided by magnetic compasses and sailing charts (portolans). The impetus to develop new instruments for navigation came from state-sponsored voyages into unfamiliar oceanic waters, beginning with the Portuguese in the fifteenth century. Specifically, Portuguese navigators returning from Guinea devised a track that involved sailing in a long westerly arc to take advantage of winds and currents, and then heading due east once they had reached the latitude of Lisbon. Latitude could be estimated straightforwardly from the height of the pole star or noonday sun above the horizon, and during the sixteenth century various astronomical instruments were simplified to do this, first astrolabes and cross-staffs, followed by the more sophisticated backstaff, devised by a sea captain John Davis in the 1590s. By this time ordinary navigators had a technology that sufficed for their purposes (backstaffs were widely used until the nineteenth century) and the development of navigational instruments largely stalled for a century.

Innovation restarted in the eighteenth century but driven now by the British Admiralty and Royal Society. Based possibly on earlier ideas of Hooke and Newton, in 1731 a Fellow of the Royal Society John Hadley developed a reflecting octant (an ancestor of the sextant) that was rapidly adopted by the Navy. After this, Britain's large naval and commercial demand for accurate navigational instruments supported a large London industry of instrument makers (Sorrenson, 1995).

Similarly, because ordinary mariners relied on traditional navigational techniques, much of the demand for the lessons in mathematical navigation offered by mathematical practitioners derived from the state in the form of young gentlemen aspiring to become officers in the navy or in state-chartered trading companies, beginning with the English Muscovy Company and the Dutch East India Company (Struik, 1981, 31–52). However, just as state intervention could stimulate navigational innovation, it could stifle it. Spain set the standards in European navigation in the mid-sixteenth century, encapsulated in Martin Cortes's comprehensive *Arte de Navegar* of 1551 which, in a simplified version by the mathematician William Bourne, remained the standard English manual until the early seventeenth cen-

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[19] Leibniz spent considerable effort "bordering on obsession" over several years in a failed attempt to design windmills to drain the Harz silver mines (Wakefield, 2010).

tury. However, the training of Spanish pilots was rigidly controlled by the Casa de la Contración and quickly became archaic by northern standards (Taylor, 1971, 250).

For simpler instruments a large private sector market emerged in surveying in the late sixteenth century, driven by the more intensive management of land, the beginnings of enclosure and land drainage schemes, and growing state interest in the potential of land taxes (Kain and Baigent, 1992). For cartography in England the decisive impetus came from the need to map land confiscated from monasteries and then the new territory gained during the conquest of Ireland (Taylor, 1954, 31–32).[20] However, as with mariners, the instruments used by ordinary surveyors were simple and changed little after the rapid innovations of the early seventeenth century: a sighting compass, a chain to mark out lengths, and a plane table for taking sights of landmarks, and sometimes a simple theodolite. Similarly for gunnery, although a variety of ranging instruments were invented, including Galileo's military compass, how often they saw use in combat is uncertain.

5.2 Astronomical Instruments.

Large state observatories equipped with increasingly sophisticated measuring instruments were established in the late seventeenth century to meet the needs of navigation, in particular the estimation of longitude by means of lunar distances.[21] The Paris Observatory was founded in 1667 for the explicit purpose of obtaining an accurate star map for lunar navigation, as was London's Royal Observatory (for "rectifying the tables of the motions of the heavens … so as to find out the so much desired longitude of places for the perfecting the art of navigation") in 1675.[22]

Just as navigation led directly to state observatories, the alternative way to compute longitude through an accurate chronometer led Hooke in the Royal Society to develop a practical spring-driven watch that was the origin for England's large and innovative watch-making industry (Kelly and Ó Gráda, 2016). This, in turn, created Britain's uniquely large workforce of watchmakers, supported by highly

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[20] Smyth (2006, 21–53) terms these Tudor maps "Instruments of Conquest."

[21] The fast movement of the moon across the background of the fixed stars makes it like the minute hand of a universal clock, so the angle between the moon and a fixed star can, with a suitable table, give the time in the ship's home port which is needed for longitude calculation.

[22] The associated French and British scientific societies in their *Mémoires* and *Proceedings* were also active in communicating details of their members' experiments including precise descriptions and illustrations of the apparatus they used that form a central part of Wolf's (1962) classic history of science and technology.

skilled and versatile toolmakers, whose importance for early industrialization we saw above.

5.3 State Privileges, Patents, and Prizes.

Besides driving the market for instruments ranging from naval sextants to observatory telescopes, the British state in the eighteenth century sought to encourage navigational innovation through prizes awarded by Board of Longitude. The Board is best known for its delayed award for John Harrison's chronometer (it also rewarded Euler at the same time for his contributions to lunar navigation), but also made frequent awards for other navigational instruments (chronometers were simply too expensive and unreliable to be of practical use until the mid-nineteenth century).

Vitally, in return for a prize, the Board required the exact details of an invention to be made public. Harrison did not receive his prize until his watch had been successfully duplicated by another clockmaker, while the astronomical instrument maker John Bird was awarded £500 on condition that he train an apprentice, and Jesse Ramsden's £615 required him to train up other, rival instrument makers in making his Dividing Engine for mass-producing the scales of sextants. Over its lifetime the Board dispensed £53,000 in rewards for innovations, and spent a further £45,000 on publications giving their details (Howse, 1998).

At the same time as the British were offering prizes for innovative technology, the French state encouraged improvement in the level of theoretical knowledge in navigation, astronomy, and practical fields such as shipbuilding through the Academy's annual essay competition. For instance, topics in the late 1760s included the satellites of Jupiter (won by Lagrange), determining time at sea (won by Le Roy, inventor of the first practical chronometer), and the movement of the moon (Euler one year, Lagrange the next): (Mandron, 1881, 21). In other words, navigation represents the first and clearest example of the Enlightenment project of creating useful knowledge through the encouragement of the state.

Patents provided an additional source of state support which were either intended to stimulate innovation or, in England's case at first, to attract foreigners with useful technical skills.[23] One particular contrast again is between England, where a large commercial market led to a demand for patents, and France where patenting was unimportant to a small industry that relied on the prestige of supplying instruments to the top stratum of science (Biagioli, 2006).

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[23] On the complex evolution of patents from royal privileges into legal rights see Bracha (2004).

For machine tools, we have stressed the importance of British innovations between 1820 and 1840. However, as the classic study of Alder (2010, 240–247; 321–338) describes the precocious and technologically promising efforts of Honoré Blanc to produce interchangeable gunlocks. Unfortunately, the exercise took place against a background in Revolutionary France of competing government factions where the temporary ascent of one group allowed the project to proceed, but it subsequently collapsed once their rivals returned to influence.

Another abortive French effort at large scale production is notable both as an episode in the history of the Enlightenment (where its human icon undertook the large scale manufacture of its technological emblem) and as a lesson in the limitations of state sponsored industry. In 1770 an exodus of striking watchmakers from Geneva allowed the 76 year old Voltaire to set up a watch factory on his estate near the Swiss border. Under his energetic management, by 1773 it employed 600 workers producing 4,000 watches and generating a revenue of 400,000 livres. However, its reliance on noble patronage could not match the commercial network of Geneva firms who lured his workers back, and the enterprise sank after Voltaire's death (Sturm and Buyssens, 2013, 1416).

6 Artisan Virtue.

Reaching its apogee in Samuel Smiles's *Lives of the Engineers* (1861) and *Industrial Biography* (1864), Victorian Britain's reverence for mechanical skill is well known. Artisans turned engineers, typically of modest background, became national celebrities: some ennobled, others made Fellows of the Royal Society, with James Watt being buried under a large statue in Westminster Abbey.[24] Less familiar is that the respect of British elites for mechanical skill goes back to the instrument makers of the seventeenth and eighteenth centuries.

In 1675, the clockmaker Thomas Tompion (1639–1713) built the first practical, balance spring watch for Hooke (who himself had been Robert Boyle's assistant) and went on to become "The Father of English Watchmaking." Despite being the son of a blacksmith, and earning his living as a shopkeeper (albeit a highly successful one) he was buried in Westminster Abbey, alongside his later business partner

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[24] Thomas Telford the civil engineer began as a stonemason and George Stephenson was a colliery engineman who was illiterate until age 18. Maudslay, the pioneer of machine tools, was first a powder-boy filling musket cartridges; while his successors Clement, Fox, and Roberts began respectively as an apprentice slater, a butler, and a quarryman, and Whitworth was abandoned by his father and raised in conditions of Dickensian squalor (Smiles, 1864). Watt and Smeaton both trained and worked at first as instrument makers.

George Graham. The son of a small farmer, Graham became Europe's foremost astronomical instrument maker (his name appears in both panels of Figure 2) and a Fellow of the Royal Society.[25]

Many of the foremost instrument makers (who usually designed the instruments they built) of eighteenth century Britain followed Graham to become Fellows of the Royal Society and some received the Copley Medal, its highest honour. Fellows included John Dollond (originally a silk-weaver; a developer of the achromatic lens), Edward Nairne (electrical machine) James Short (father a joiner, telescope maker); Edward Troughton (father a small farmer, Copley Medal for dividing scales of observatory instruments 1809). The most famous European instrument maker of the late eighteenth century was Jesse Ramsden (father an innkeeper, Copley Medal 1795).[26] Although not a Fellow, the carpenter and clockmaker John Harrison received the 1749 Medal for one of his early chronometers.[27] It should be emphasized, of course, that although some leading instrument makers were respected by gentlemen natural philosophers as their intellectual peers, we are not suggesting that they were in any way regarded or treated as their social equals.

In contrast to the prestige of English instrument makers, the attitude of European scientists to their assistants, going back to the seventeenth century, is largely one of frustration. In attempting to make lenses, both Descartes and Huygens were hampered by the low standard of the craftsmen they commissioned. Descartes had to abandon efforts to build a sophisticated machine that he had designed to grind hyperbolic lenses; and Huygens was reluctantly compelled to become an accomplished lens grinder (Burnett, 2005).

The closest that France came to recognising artisan skill, the Société des Arts (1728–1736), was driven from below by artisans and soon collapsed for lack of upper class patronage (Bertucci and Courcelle, 2015); and, as noted earlier, France's greatest watchmaker, the Englishman Henry Sully, was denied membership of the Academie notwithstanding the support of Leibniz.[28] The attitude of some Conti-

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[25] This regard was not uniform, especially in the seventeenth century when the Royal Society treated many of its demonstrators poorly (Pumphrey, 1995); and Hooke, in a race against Huygens to build a spring-regulated watch, berated Tompion as a "Slug", and a "Clownish Churlish Dog" for working too slowly: Sorrenson (1999). Boyle's distaste for his assistants is detailed by Shapin (1994, 355–407) but this must be balanced against his regard for the expertise of the "glass-men" who made his laboratory instruments: Buchwald and Feingold (2013, 62–63).

[26] In tracing the rising prestige of English innovators after 1750 from dubious projectors to heroic inventors, MacLeod (2007, 74) notes Tompion and Graham, but neglects these later figures.

[27] This fact is overlooked, even by Landes (1983), in accounts of Harrison as the heroic outsider taking on the British scientific establishment.

[28] The contributions of the more enduring British Royal Society of Arts, founded in emulation of the French institution are detailed by Howes (2020).

nental *savants* towards their *fabricants* is encapsulated by the French Astronomer Royal Jean-Dominique Cassini. On a visit to London in 1787 to order observatory instruments from Ramsden (whom he addresses in their correspondence with marked deference), he concluded that whereas the leading British makers "… are geometers and physicists, our best craftsmen are merely labourers" (Wolf, 1902, 287–300).

Naturally, although Diderot's *Encyclopédie* gives compendious illustrated entries for technological topics, it is important to realise, as Koepp (1986) observes, that alongside the goal of understanding and improving useful knowledge runs a desire to have technology reduce the role of artisans to virtual automata in the service of savants. However, a more nuanced view of French attitudes to artisan virtue, outside the Enlightenment elite, emerges in the *Le spectacle de la nature* (1732–1751) of Abbé Puche, one of the leading bestsellers of eighteenth century Europe running into at least 57 editions in French and 27 in English, besides translations into French, German and Italian; and is the fourth commonest title recorded in contemporary catalogues of Parisian private libraries (Mornet, 1910).

Although now little known, this eight volume work in an affordable *petit format* prefigures Diderot's work in its range of topics and extensive illustrations, almost all of manufacturing and machinery. Although it includes lengthy and well informed discussions of contemporary physics and astronomy (including Newton and Copernicus), its stress is on generating useful, empirically based knowledge. Throughout, Puche emphasizes the need to respect the dignity and skill of ordinary artisans, noting for instance that "True merit consists in work and industriously serving the good of society", and insisting that the only way to understand the technology that continually raises humanity further above primitive chaos is from first hand knowledge gained by personal contact with artisans in their workshops (Koepp, 2007).

7 China and the Islamic World.

We have seen how the development of measuring instruments—often with direct state support—ranging from utilitarian navigational and surveying instruments (and later watches) at one end, to large astronomical instruments at the other, eased the progress of British industrialization, first in textiles and steam, and then in machine tools. It is worth asking to what extent China and Islam failed to derive similar technologies and why.

7.1 Navigation.

The traditional view that Chinese maritime trade was seriously hampered by state restrictions (see for example Jones 1981, 204–205) is a considerable over-simplification. Certainly, between 1372 and 1576 private trade was formally prohibited, but the ban was enforced intermittently and circumvented widely. Even when bans were effective, official trade was still permitted through the "tribute" system which, in practice, often entailed foreign merchants posing as "political emissaries" who would pay "tribute" as a cover for private commercial transactions (Frank, 1998, 114).

In navigation, the geographic overlap of their trading zones ensured that Chinese and Islamic practices were closely related. Navigators relied on compasses, and also on measuring the angle of the pole star above the horizon, a technique already in use by the time of Ibn Majid, the prolific fifteenth century writer on navigation. The basic tool, the kamal, was a card of rectangular wood attached to a knotted string that the navigator grasped in his teeth. The card was moved out until it just covered the distance between the pole star and the horizon, so by counting the number of knots, each a finger width apart, the navigator could estimate his latitude (Needham, 1970, 40-70; Agius, 2008, 196-202).

However, navigational innovation then stalled, possibly because existing technology was sufficient for the predictable monsoon sailing on fairly calm seas undertaken by Islamic and Chinese sailors. The lack of government interest in developing oceanic navigation (excepting, of course, the famous but extremely expensive expeditions of Cheng Ho) of the sort shown by the impoverished and expansionary states of Atlantic Europe meant that the large scale production of carefully graduated navigation instruments never took off. King (1992), in his extensive survey of Islamic instruments, notes that "most important contributions to instrumentation were made by individuals working alone" and his subsequent list shows that important centres of instrument making were widely dispersed in time and space. The large concentrations of instrument makers of the sort that had emerged in England or the Netherlands by the late seventeenth century had no parallel in the east.

7.2 Astronomy.

Turning from applied navigation to scientific astronomy, Islam, of course, served as the conduit through which Hellenistic astronomy reached Europe. However, despite considerable advances in instruments (especially in astrolabes and instrument sights) over those described by Ptolemy, and several observatories built with extremely large instruments, with exceptions such as Taqi al-Din the initiative in astronomical development had shifted to the west by the fifteenth century (Bennett, 16–17; King, 2012).[29]

Although notions of China as some timeless, unchanging polity have long been abandoned, there is one aspect of Imperial ideology that did remain fixed over much of its history: the view that astronomy was a political activity that required assiduous control by the state. In Europe and Islam from medieval times the science of the stars was viewed as an activity of religious and practical importance—for Christianity for determining the date of Easter and the correct times of Monastic Hours of prayer (McCluskey, 1998, 77–113); and in Islam for determining the direction of Mecca, and the hours at which prayer was forbidden (Dohrn-van Rossum, 1998, 30–31); as well as astrology in both. In China, by contrast, astronomy mattered because it directly underlay the legitimacy of the Son of Heaven.

Specifically, in 1045 BCE the Zhao Dynasty justified its usurpation of power from the reigning Shang on the grounds that the latter had forfeited the Mandate of Heaven, and thus created a powerful and enduring ideology of political accountability, one with no counterpart elsewhere (Zhao, 2015, 52–55). Astronomical events that had not been predicted—such as comets, novae, and especially eclipses—were portentous indications of possible heavenly displeasure. This meant that producing an accurate calendar to keep "All under Heaven" harmoniously regulated (by predicting as many celestial events as possible, as well as providing auspicious days and times for political, agricultural and other activities) was a fundamental duty of the Emperor, laid down in the Five Classics (Elman, 2005, 102).[30] Official calendars were therefore published in large numbers—2.7 million, or one for every seven households, were distributed by the state in the late Ming, besides commercially printed ones (Elman, 2005, 111)—a task undertaken by the official Astro-Calendrical Bureau.

Controlling astronomy through a mid-ranking government department meant that China lacked the the technical expertise to reform the calendar whenever it moved out of synchrony with the heavens, as it had when Jesuits arrived in 1582. Fresh from the calculation of the Gregorian calendar and having received instruc-

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[29] Taqi al-Din's large observatory in Istanbul was demolished in 1580. That this represents an instance of "The Triumph of Fanaticism" over Islamic science is disputed by El-Rouayheb (2008).

[30] Technically the calendar was an ephemeris, listing the position of the sun, moon, and visible planets at given times for each day of the year. Needham, Wang and Price (1986, 7–8) note that the discovery that Liao "Barbarians" had more accurate astronomical predictions than the Sung Chinese motivated the construction of Su Sung's famous clock.

tion in mathematical astronomy as part of their routine training, Jesuits saw reform of the Chinese calendar as a means to gain influence in the Imperial Court.

Jesuit astronomy in China culminated in 1670 with Ferdinand Verbiest's construction of a sophisticated observatory with the assistance of local artisans. Visiting in 1687, a fellow Jesuit concluded that the workmanship of the Chinese craftsmen who built the instruments was exemplary, but for one critical defect: the quality of the scale graduations was extremely poor (Chapman, 1984). In other words, a fundamental technical capability developed in Europe and especially in Britain—the creation of a large workforce of instrument makers whose mechanical dexterity easily transferred to other industrial activities—did not exist in China. As a result, even if official hostility to private astronomy may sometimes be overstated, there is no question that the lack of state encouragement to innovation in observatory instruments and navigational practice seriously hampered these important sources of technological capability.

8 Conclusions.

For Francis Bacon the three decisive inventions since classical times were famously "printing, firearms and the compass". Two hundred and fifty years later, by contrast, after noting how each science is defined by the precision instruments it employs, James Clark Maxwell (1871, 75) concluded that "…the whole system of civilized life may be fitly symbolized by a foot rule, a set of weights and a clock."

A direct line of expertise in making instruments ranging from simple surveyors' tools to observatory telescopes connected the Scientific and Industrial Revolutions. Naturally, we are not making any claims that instrument making was in any way "the cause" of the Industrial Revolution, simply that the widespread mechanical expertise that it called into being greatly facilitated the development of later factory technology, first in textiles and steam, and then in precision manufacturing.

Throughout we have seen how misleading simple dichotomies can be. Instead of artisans versus philosophers, we saw how both groups fused together through practical mathematics. Instead of Protestant science versus Catholic obscurantism we saw enthusiasm towards of astrology stimulated mathematical teaching in Lutheran universities and antagonism towards it caused its separation from mathematical astronomy in Jesuit textbooks. Instead of incentives versus capabilities we saw how each fed off the other with opportunities creating technologies that opened further opportunities: state demand created a supply of mathematical practitioners who developed technologies that later facilitated industrialization.

When it comes to explaining the ultimate economic success of Europe and especially Britain, the role of a distinctive culture of improvement and systematic empiricism has been stressed by Mokyr (2011; 2016) and Jacob (1997), and the role of bourgeois values by McCloskey (2006). Here we have drawn attention to an important group of applied mathematicians and instrument makers who connected the worlds of natural philosophy, mathematics, and astronomy with the practical needs of navigators, surveyors, bookkeepers and others using measurement in their daily work. In particular we stressed how the practical mechanical skills of artisan instrument makers fed into early machine building, and the measurement technology of astronomical instruments into the less well known and typically misunderstood British development of machine tools and precision manufacturing.

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