CHAPTER

25

Attitudes, aptitudes, and the roots of the great enrichment

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25.1 Introduction

The term "Great Enrichment" proposed by McCloskey (2016, p. 5) should be regarded as a better term to describe the hockeystick-like time series of income and living standards after 1800 than the "Great Divergence" proposed by Pomeranz (2000). The latter is a statement about *relative* income between the West and the Rest, whereas "enrichment" points to the world-wide increase in almost every measure of living standards than one can think of. But what drove that divergence were the unprecedented events that started in western Europe in the eighteenth century and that started the ball rolling — and rolling it still is. The economies that fell behind the West in the nineteenth century have experienced dramatic improvements in absolute terms as well, even if the income per capita gaps are still profound. If poverty is now declining world-wide, the "deep" reason is the growth of what Europeans called "the useful arts" or "useful knowledge."

The dynamic process leading to the Great Enrichment and its timing matter a great deal. Scholars of the fundamentalist Malthusian school such as Clark (2007) and Galor (2011) have argued that prior to the Industrial Revolution there was little or no growth in income per capita and that all improvements in productivity were, in H.G. Wells's (1923, p. 68) famous formulation, wasted "as rapidly as it got them in a mere insensate multiplication of the common life." But recent work has raised effective criticism against these interpretations. Voigtländer and Voth have noted the possibility of multiple equilibria in a Malthusian system due to urbanization and changes in agricultural practices, whereas Dutta et al. (2018) show that in a Malthusian world with luxury products, living standards can rise without being undone by relentless population growth. The new data summarized by Broadberry et al. (2018) show remarkable long term growth in many pre-modern economies. To be sure, many of these economies eventually reached some kind of plateau (but at very different levels) but the reasons for stagnation include other factors as well (Mokyr, 2018).

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25.2 Europe and the world

Trained economists will find it surprising that there is a school of historians who still regard modern economic growth primarily as a case of successful predation, according to which the West enriched itself at the expense of other civilizations that were less committed to capitalist practices and less aggressive. While they rarely use the term, these scholars see the Great Enrichment fundamentally as a zero-sum game, in which colonial plunder and enslavement enriched a few nations in Europe at the expense of the rest of humanity (e.g., Inikori, 2002). State actions, often driven by mercantile political influence led to the forceful seizure of Atlantic markets by British and French agencies, and the technological progress that occurred was the outcome of an "explicit rejection of market outcomes" (Parthasarathi, 2011, pp. 143, 62). Others see the European expansion after 1500 as creating a web of commercial and financial relationships engendered by the Atlantic slave trade, which prove a critical factor in Britain's capitalist industrialization, further assisting its global supremacy.[1] Equally explicit is Sven Beckert's much-praised volume on the history of cotton (Beckert, 2014), who explains Europe's economic successes by a "coercive European mercantile presence in many of the regions of the world" (p. 37) and asserts the existence of something he calls "war capitalism," by which he means the combination of imperial expansion, slavery, and land expropriation (p. 52) as the engines that drove dynamic markets, capital formation, and eventually innovation and economic growth in the West.

The "history of capitalism" notion of capitalism red in tooth and claw as the dynamic force behind the Great Enrichment, in its haste to distance itself from any interpretation that could be accused of "Eurocentric" or "triumphalist," essentially abstracts from the deep changes in Europe that made it possible. Nobody will deny the salient facts of colonialism, slavery, and the ruthless domination and exploitation of non-European populations. But the exact causal chain behind the Great Enrichment is simply too important to be glossed over in a wave of ideological zeal by those who see a malevolent force named "capitalism" as the primary force behind global imperialism and inequality. This literature seems to assume that given of the devastating effects that European domination often had on the colonized, there must have been proportional gains to the perpetrators. But as McCloskey (2010, pp. 229–48) and many others have pointed out, this interpretation is still based on an implicit zero-sum image of the world. In economic history, zero sum games are exceedingly rare. Violence, trade wars, conquests, and exploitation are negative sum, trade and technological progress are positive sum.

Much more plausible is the causal chain suggested by Daniel Headrick (1981, 2012), who shows in detail how western technology made colonialism possible (as opposed to the other way around). European military technology remained ahead of that of the rest of the world, in large part, because Europe was fragmented into large and small units that fought each other almost incessantly. These wars led to growing investment in weapons and through learning by doing and competitive pressures, Europe developed military hardware and organizational capabilities that gave it an edge in its battles with non-western adversaries (Hoffman, 2015). Superior technology made it possible for Europeans to enslave Africans, ship them across the Atlantic, and make them work in plantations in the new world. Slavery was an essential part of a global act of ecological and economic arbitrage, in which European ships sent new world crops to Asia and Africa as well as to Europe itself (Nunn and Qian, 2010).

[1] Anievas and Nisancioglu (2015, pp. 121–122) argue that the "limits of 17th-century English agrarian capitalism" could be overcome because England's "ruling class was able to exploit the widened sphere of economic activity offered by the Atlantic."

Yet a simple causal chain that runs from technology to arbitrage and colonialism leaves us dissatisfied, because the *primum movens* remains mysterious. Why did Europeans, at least for many years, outperform other civilizations technologically and what allowed them to subjugate, rob, and exploit non-Europeans, from Peru to the Gold Coast to Java? It just cannot stand up to scrutiny to assert, as does Parthasarathi (2011), that as late as 1750 Europe and India were at comparable levels of development. One might well ask the unanswered question that "Had Britain and India been at the same level of economic and institutional development in 1750, why was there no 'Western Europe Company' set up in Delhi that would have exploited the political divisions within Europe, established an Indian "Raj" based in London that forced Europe to accept Indian calicoes without tariffs?" (Mokyr, 2012).

The same question was already asked at the time. In an interesting (and widely cited) passage, Dr. Samuel Johnson's fictional Abyssinian prince Rasselas asked his philosopher friend "by what means are the Europeans thus powerful; or why, since they can so easily visit Asia and Africa for trade or conquest, cannot the Asiatics and Africans invade their coasts, plant colonies in their ports... the same winds that carry them back would bring us thither." The answer that was provided would horrify ideologically pure historians of capitalism: "they are more powerful than we, sir, because they are wiser; knowledge will always predominate over ignorance. But why their knowledge is more than ours I know not" (Johnson, 1759, Vol. 1, p. 74). Yet question "why" is not unanswerable; by 1750, surely, Europeans knew more than non-Europeans about subjects that affected or would soon affect economic performance and material living standards. The summary answer to Johnson's question is differences not in "wisdom," as the philosopher surmised, but in *attitudes* and *aptitudes*, that is cultural beliefs and technical competence. Both of these were the result, and in turn causal of, differences in institutions.

25.3 Attitudes

Since Greif's pathbreaking paper (1994) it has been recognized that cultural beliefs matter a great deal to the formation and operation of markets and the expansion of commerce. The importance of such concepts as general vs. local morality and trust as a means of saving on transaction costs and supporting markets have been widely recognized. But what about useful knowledge, that is, the understanding of natural phenomena and regularities that lent themselves to being harnessed for productive purposes? Past societies have differed in their willingness and ability to introduce technological innovations that led to creative destruction and possibly social instability as the price of higher productivity and living standards. It stands to reason that *institutions* mattered a great deal here, providing incentives and support for entrepreneurs and inventors and a safety net for workers whose earnings were disrupted by technological progress. But what about attitudes? Religion and a vision of nature surely mattered. An anthropocentric view of the world, in which nature was regarded as an exploitable resource and where its manipulation and disruption by humans were regarded as inherently virtuous and an expression of God's will were surely at the base of a technologically aggressive society. A famous example of such an interpretation is the work of Lynn White (1978), who saw the roots of technological progress in the doctrines and institutions of the medieval Latin Church.[2]

[2] If metaphysical beliefs are such that manipulating and controlling nature invoke a sense of fear or guilt, technological creativity will inevitably be limited in scope and extent. The legends of the ill-fated innovators Prometheus and Daedalus illustrate the deeply ambiguous relationship between the ancient Greeks' religious beliefs and their attitudes toward technology.

One of the most striking examples of how cultural beliefs affect scientific and technological progress is the inferiority complex with respect to ancient wisdom. Intellectual ancestor worship was one of the most underrated obstacles to technological progress. A famous dictum from the Jewish *Chazal* (earlier sages) has it that "if those who were before us (*rishonim*) were like angels, we are but men; and if those who were before us were like men, we are but asses" (Sabbath, 112b, see for instance https://en.wikipedia.org/wiki/Yeridat_ha-dorot).[3] This was not, in its basic outlook, inherently different from the attitudes in China toward the founding intellectuals of Chinese philosophy Confucius, Mencius, and Xunzi, and that of Moslems for the Quran and the *Hadith* (sayings attributed to the prophet Muhammad compiled in the 8th and 9th centuries). The veneration for ancient knowledge had a distinct dampening effect on the ability of society to experience knowledge progress, since it imposed constraints on what new knowledge was and was not permissible. It created a rigid box, and thinking outside that box could entail accusations of heresy.[4] Within the box, there still could be lively debates and discussions, but they were seriously constrained.

One of the most dramatic developments in Europe's cultural life after 1500 was the slow but inexorable melting away of this inferiority complex and the rise of heterodox ideas in a host of areas. Medieval science was not nearly as stagnant and as homogeneous as it is often portrayed.[5] But it was hamstrung by primitive instruments and inaccurate measurement, the fear of being accused of apostasy, and the legacy of classical science, above all Aristotle, Pliny, and Galen. In the later Middle Ages a powerful syncretic orthodoxy had been established that merged Christianity with Aristotelian philosophy and classical science, the monumental life's work of Thomas Aquinas. Renaissance scholars discovered more and ancient scientific writings and made them part of their world-view. A few early doubts cast on the orthodoxy can be seen already in the early Renaissance.[6] Yet only after 1450 did deep cracks in this structure start to emerge, and in the next centuries it showed serious signs of weakening. An early example was the devastating attack on Pliny's scientific work launched by the Ferrara Professor Niccolò Leoniceno in 1492. In the middle of the sixteenth century, the French philosopher Pierre de la Ramée (1515–1572) already wrote freely "on the errors of Aristotle" and by the early seventeenth century Francis Bacon insolently wrote that "[the Greek writers of science] certainly do have a characteristic of the child: the readiness to talk with the inability to produce anything; for their wisdom seems wordy and barren of works" (Bacon [1620] 2000, aphorism 121, p. 59). Without skepticism, there could be no progress.

By the late seventeenth century, at the dawn of the Enlightenment, European intellectual respect for the science of the ancients was largely gone. The slogan of the Royal Society, *nullius in verba*

3 The Hebrew expression *yeridat hadorot* means literally the decline of generations, that is, a sense of inferiority compared to earlier sages and an unwillingness to challenge them. It is quite widespread in the rabbinical literature.

4 As Carl Becker noted in a classic work written in the early 1930s, "a Philosopher could not grasp the modern idea of progress ... until he was willing to abandon ancestor worship, until he analyzed away his inferiority complex toward the past, and realized that his own generation was superior to any yet known" (Becker, 1932, p. 131).

5 One fierce debate between the natural philosophers and the theologians concerned the questions of the eternity of the world and whether there were any limitations were imposed on God's powers by the laws of nature.

6 One of them concerned Aristotle's laws of motion. The 12th-century Andalusian philosopher Ibn Bajja (known as Avempace in the Christian world) already saw the flaws in Aristotle's theory and his ideas found their way to the writings of Aquinas himself. Other medieval scientists such as Nicolas of Oresme and John Buridan also criticized some details of Aristotelian physics. That said, the consensus remains that "only in the sixteenth and seventeenth centuries was Aristotelianism seriously challenged" (Grant, 1996, p. 88, citation on p. 162).

(on nobody's word) could well have been applied to the dominant parts of European intellectual life. True, in the late seventeenth century both France and England witnessed a *querelle des anciens en des modernes* — a battle between the ancients and the moderns (Levine, 1981, 1991; Lecoq, 2001). But any notion that this battle ended in a draw, as Swift implied in his priceless parody of the debate (Swift, [1704] 1753, p. 170), is mistaken: by the late seventeenth century Newton and his contemporaries had hammered the last nail in the coffin of ancient physical science.[7] It was more than physics. The Florentine physician Francesco Redi (1626–1697) showed convincingly that the Aristotelian belief in spontaneous generation of plants and insects was false and William Harvey (1578–1657) showed the same for the Galenic model of blood circulation.

To what can we attribute this rather unique cultural turn? One of them is rather obvious: from the late fifteenth century on Europeans were repeatedly confronted with discoveries that contradicted the received wisdom of the ancients, making classical science continuously lose credibility. In part this was due to the great voyages, which showed that the earth was not what Aristotle and Ptolemy had described. Whereas Copernicus was still basing his revolutionary view of the universe on known facts and theory, Galileo was able to prove him right through his ability to discern the phases of Venus.[8] From Paracelsus to Andreas Vesalius to Galileo and William Gilbert, early-modern European scientists felt free to criticize classical medicine and science, and suggested new theories incompatible with the ancients. New scientific instruments and tools, unavailable to classical philosophers, underlined the superiority of the moderns who rightfully argued that they could observe phenomena and see things that the ancients could not. By the mid seventeenth century, even the holy bible itself did not escape dispassionate textual analysis despite fierce indignation by devout clerics of various stripes.

The change in attitudes was driven in part by institutional change. The new discoveries would not have been effective in overthrowing the classical orthodoxy had it not been for an environment in which intellectual innovation was rewarded and incentivized and moreover could not be effectively suppressed by conservatives and vested interests. A new set of institutions (above all the Reformation), improved technology (above all the advent of the printing press and the decline in transportation costs), and the rather sudden appearance of new information with the great voyages encouraged out-of-the-box thinking that led to the rapid proliferation of intellectual innovations. The market for ideas became more active and more competitive, especially when the monopoly of the Catholic Church collapsed after 1517. Like every market, the market for ideas needed an institutional foundation that defined the basic rules of the game and allowed it to function effectively.

The sixteenth- and seventeenth-century market for ideas in early modern Europe consisted of a demand side based primarily on patronage by princely courts and wealthy individuals, and by other institutions such as universities and academies. Success was correlated with reputation — mostly created by peers who were in the best position to evaluate scientific work (Dasgupta and David, 1994). Reputation in turn correlated with financial security and social standing. University appointments, then as now, were an important component of patronage for intellectuals, and the desire for a secure and comfortable income (if not riches) was a main driver of scholarly efforts. Some of the court patronage appointments are well-known, such as the Grand Duke of Florence, who employed Galileo as the court scientist, and that of the Habsburg Emperor Rudolf II in Prague, who employed not only the

7 Swift concluded that "we cannot learn to which side Victory fell" (Swift, [1704] 1753, p. 170).

8 Tycho Brahe's well-known observation of a nova (refuting Aristotle's belief of an fixed and unchanging sky) and the demonstration that nature, after all, does not abhor a vacuum cast further doubt on the infallibility of ancient wisdom.

great astronomers Brahe and Kepler, but also botanists like Carolus Clusius, (né Charles de l'Écluse 1526–1609).[9] Louis XIV, always keen on bolstering his international image, attracted to the French Royal Academy some of the great superstars of the age such as the Dutch mathematician Christiaan Huygens and the Italian astronomer Giovanni-Domenico Cassini, as well as French scientists such as the architect and anatomist Claude Perrault (1613–1688) and the Abbé Jean Picard (1620–1682), the first person to measure the size of the Earth with a reasonable degree of accuracy. Many lesser rulers and wealthy nobles similarly extended patronage to leading scholars.

The demand for scholars had a practical side. Many of the most successful practical intellectuals in early modern Europe had been trained as physicians and were employed in that capacity by their patrons. Mathematicians and physicists could help with military matters.[10] Others were employed as tutors, most famously René Descartes at the court of Queen Christina of Sweden.[11] Still others were political counselors, even if their mathematical and philosophical skills did not always match their political insights, as was the case with Leibniz, an advisor to the Duke of Brunswick. Equally in demand were physicians.[12] In all of those cases, reputations — as established through publication and correspondence with peers — were decisive to ensure an appointment. The demand side was thus highly competitive.[13]

On the supply side competition was equally fierce. Intellectuals shamelessly pandered to wealthy patrons, dedicating their books to them and writing fawning prefaces thanking their benefactors. Being a member of a court provided security and protection, but also involved a rise in social standing. It mattered for scientists and artists to be recognized by figures of high social standing and power, because such recognition conveyed respectability in an age in which outside the scholarly community "whom you knew" conveyed as much social prestige as "how much you owned" (Hahn, 1990, p. 7). Biagioli (1990) has made this a central argument in his "new view" of patronage, in which he explicitly tried to minimize the economic motives that drove scientists. Instead he argued that the incentive that drove them was being associated with the mighty and rich elite that provided scientists with "social and intellectual legitimacy." Patronage in this view was a means to an end. While such legitimization may have been important in some cases, it would be rash to dismiss material motives in an age in which many talented scholars found it difficult to earn a living. All the same, the patronage transaction was clearly a multidimensional exchange.

What made this market work, and what ultimately drove the market for ideas, was an underlying institution that set the rules of the scholarly game that were accepted by the vast majority of participants.

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9 Clusius, one of the founders of modern botany, was learned, cosmopolitan, widely traveled, and well-connected. He worked for both Rudolf II and Rudolf's father Maximilian II (Evans, 1973, pp. 119–20).

10 Galileo, while still working in Padua, freelanced for the Venetian arsenal and in the late 1500s invented a geometric and military compass (used for gunnery), as well as other militarily useful devices.

11 Thomas Hobbes was originally hired by the Cavendish family to teach their children, as was the mathematician William Oughtred, who was a member of the household of the earl of Arundel.

12 The astronomer and physician Jean Fernel (1497–1558) served as the king's personal physician at the court of Henry II and the physician and polymath Pierre Michon Bourdelot (1610–1685) served as the personal physician of Queen Christina of Sweden. Both William Gilbert and Francesco Redi were well-known physicians even if their contributions to knowledge were elsewhere.

13 An example is the distinguished Florentine mathematician Vincenzo Viviani (1622–1703), a student and protegé of Galileo in his later years. In 1666 his reputation was such that he was offered lucrative positions by both Louis XIV and John II Casimir of Poland, whereupon Grand Duke Ferdinand de Medici made him a counteroffer and appointed him court mathematician.

It was not a formal, state-run institution but a virtual international network of scholars sharing interests and scholarly ambitions.[14] Known to its members as the "Republic of Letters," it served simultaneously as a clearinghouse and sounding board for scholarly work written in Europe. It served as a mechanism to evaluate intellectual innovations and indirectly the reputation of scholars and intellectuals. The vast bulk of the intellectual innovators recognized by posterity as having made major contributions to science were already world-famous superstars in their own time, no one more so than Newton himself. The Republic of Letters ensured the emergence of open science, since keeping discoveries a secret would do little for a scholar's reputation.[15] It surely is true that scientific knowledge that is kept secret can hardly contribute to economic progress, and that the emergence of open science was the critical development of the age (David, 2008). By reducing the secretiveness of knowledge and turning useful knowledge into what today would be called an open-source system, European intellectuals created an institution that reduced access costs. But it is only in a community that is both competitive and collaborative — such as was the case in a comparatively free market for ideas — that genuine progress was achieved and that the knowledge-foundation of the techniques that drove the Great Enrichment was laid.[16]

In this competitive environment, paralyzing intellectual ancestor worship had little chance of surviving despite stubborn rear-guard actions by conservative writers defending the "ancients." The most desirable sign of success was *influence*, that is, success in persuading others of the merits of a new idea or theory. Such influence depended on the rhetorical rules of science determined (if informally) by the Republic of Letters. Persuasion increasingly turned from finding textual support in the traditional books in the "canon" to observations, experiments, and logic (including mathematics). Transitions were slow and gradual, and even when ancient truths were overturned, it was often hard to abandon Aristotelian and other antiquated concepts such as astrology and numerology altogether. William Harvey, whose discovery of the circulation of the blood challenged age-old fundamental physiological doctrines still adhered as much as he could to Aristotelian methods (Cook, 2006, pp. 425–426). Yet even Aristotle's immense prestige in the end was not sufficient to save the ancients. By Galileo's time, Gillispie has observed, the science and authority of Aristotle had "led the western mind to a dead end" (Gillispie, 1960, p. 11).[17] Innovative natural philosophers, in their eagerness to impress one another (and hence

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[14] Some of the following is adapted from Mokyr (2016), chapter 12.

[15] Science was seen as a "hunt," a metaphor that appealed to the upper class patrons of philosophers in search of employment (Eamon, 1991, p. 27; 1994, pp. 269–300).

[16] To be sure, intrinsic motivation — curiosity and a desire to make the world a better place — continued to play a role in motivating intellectual innovators. The human need to be respected by peers played a role beyond the competition for patronage positions. Robert Boyle was one of the richest men in England, but this did not stop him from getting annoyed by people using his work without attribution (Shapin, 1994, p. 183; Hunter, 2009, p. 190). In the Netherlands, Spinoza diligently made his living grinding lenses (supplemented by funds from a few admirers), while gradually establishing a continent-wide reputation as a radical (and highly controversial) philosophical innovator. His contemporary, the microscopist Anthonie van Leeuwenhoek, a well-to-do draper and official, communicated his scientific findings (written originally in Dutch) to the Royal Society in London, which published many of his letters. In 1680 he was elected a Fellow, and clearly this was a source of pride for him, as he had it engraved on his tombstone and a painting of him by Jan Verkolje shows him proudly displaying his Royal Society diploma of membership.

[17] Modern scholarship may take issue with Gillispie's judgment that while Aristotelian physics "made sense of the world" it suffered from one major defect: it was wrong (1960, p. 13). It seems more plausible that it eroded because new and indisputable evidence inconsistent with its propositions was discovered.

indirectly those who would extend patronage to them), increasingly dared to criticize the conventional wisdom, and if they only could, shot it to pieces.

Intellectual property rights assumed the form of priority rights: the first person to enunciate a new idea theoretically received the credit for the new idea and the concomitant reputation effects. The system, of course, worked far from perfectly, but it worked well enough to establish the reputation of dozens of intellectual superstars active in Europe in the years between Erasmus and Newton. Priority fights were the natural consequence of the competition for priority in the market for ideas. As Wootton (2015, p. 96) summarized, "priority disputes are an infallible indicator that knowledge has become public, progressive and discovery-oriented"[18]

Progress occurred, but the new interpretations did not invariably offer what posterity would judge to be improvements on existing knowledge: the iconoclastic Swiss physician Paracelsus and his seventeenth century follower Jan-Baptist van Helmont dismissed Galenian medicine, but in retrospect it is hard to conclude that the iatrochemical school they established constituted a dramatic improvement in terms of its clinical outcomes. Similarly, there was the influence of phlogiston theory, proposed by German scientists in the late seventeenth century replacing the four elements of the Greek classics by a new set of elements, one of which was phlogiston that flowed out of a material when it burned. Yet the eventual transformation of chemistry in the age of the Industrial Revolution is emblematic of how the competitive market for ideas worked. When the experimental work of Lavoisier and his students in the late eighteenth century showed unequivocally that phlogiston theory was erroneous and inadequate, it was discarded.

Europe's intellectual progress between 1500 and 1700 paved the road for the subsequent prosperity it was to enjoy, as well as for its ability to dominate, colonize, and exploit other civilizations. The success of its market for ideas, however, in generating this progress was the result of neither design nor intent, but a classic "emergent property," the macro-level system-wide unintended consequences of lower-level interactions. What made Europe the birthplace of the Great Enrichment was a unique set of circumstances, many of them quite accidental. Europe was highly politically fragmented, with city states, and small duchies and bishoprics interspersing larger nation states. Fragmentation has often been credited as a key to Europe's success (see Jones, 1981, pp. 104–126 for a canonical statement and Scheidel, 2019 for a more recent analysis). Between 1500 and 1700 European polities were constantly at war with one another. The customary dynastic squabbles were compounded by the Reformation, which created another casus belli in Europe, and aggravated dynastic and colonial conflicts.

And yet the political fragmentation of Europe was indispensable for its intellectual development. The reactionary forces and entrenched incumbents in Europe defending the ancients against "heretics" faced an almost impossible coordination problem. Much as the Jesuits, for instance, would have loved to suppress Copernican astronomy and infinitesimal mathematics (Alexander, 2014), they could not impose their will north of the Alps. Above all, iconoclastic intellectuals moved on the seams between polities and religions and expertly played the great powers against one another. Suppressing non-conformists became almost impossible, as scholars found it easy to circumvent censors by publishing their work abroad, and when necessary could themselves move across the border, where their

[18] Most famous, of course, was the fight between Newton and Leibniz on the development of infinitesimal calculus. Equally nasty, if more obscure, was the fight between two Dutch scientists, Jan Swammerdam and Reinier de Graaf, over the discovery of a technique to study female reproductive organs around 1665. According to an unsubstantiated account, De Graaf died as a result of the exhaustion caused by the priority dispute (Cobb, 2006, pp. 184–85).

international reputations often meant a warm welcome and a nice pension. Once the knowledge of the futility of suppression sank in, the suppression of unconventional thought dwindled down to window dressing. As a result, despite some local defeats, at the end of the day the moderns decisively won the *querelle* with the ancients.

The Republic of Letters created an intellectual institution that was truly transnational and that ensured that every scholar catered to a continent-wide constituency.[19] European intellectual life thus enjoyed the benefits of both a polycentric political system and the economies of scale of a continent-wide community of scholars. The long-run benefits to the growth of knowledge were substantial. The centuries-old monopoly of Christianity on the European market for ideas, protected by the effective use of the concept of heresy, slowly receded. The Republic of Letters is an illustration of Cipolla's (1972, p. 52) insightful remark that the same qualities that make people tolerant also make them receptive to new ideas.[20]

One of the great winners in the increasingly effective and active market for ideas was a belief in progress. Not just progress in knowledge as argued by the *modernes* but also economic progress and even social and political progress toward more harmonious institutions and a better society, as enunciated by the more ebullient Enlightenment writers.[21] Much of the latter eventually turned out to be illusory. The only areas in which there can be little doubt that the improvement was real and demonstrable were technological progress and economic growth. The attitudes and beliefs that prevailed in the early modern market for ideas created the historical phenomena that eventually led to the Great Enrichment: the Scientific Revolution, the Enlightenment, and the Industrial Revolution.

How crucial was the knowledge produced by natural philosophers in the European Republic of Letters to the Industrial Revolution? The debate on that matter is still far from settled. Early modern Europe made many advances that are now recognized as milestones in our understanding of nature, but relatively few of them found an application in the early inventions in the Industrial Revolution, especially in the cotton industry. Yet before dismissing the role of science in the Great Enrichment as done by McCloskey (2010, ch. 38), three matters should be considered. First, even in the early stages of the Industrial Revolution there were some notable triumphs attributable to what we would regard today as scientific knowledge, especially if we include practical mathematics: hydraulic and steam power, chlorine bleaching, gas lighting, longitude determination, surveying instruments, slide rules, and smallpox inoculation should all be placed in that category (Kelly and Ó Gráda, 2020). To be sure, in many of those cases the epistemic base on which the techniques rested were incomplete and

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[19] Edward Gibbon observed that the philosopher, unlike the patriot, was permitted to consider Europe as a single "great republic" in which the balance of power may continue to fluctuate and the prosperity of some nations "may be alternately exalted or depressed." But this concept of a single "great republic" (intellectually speaking) coupled to political fragmentation guaranteed a "general state of happiness, system of arts and laws and manners." It "advantageously distinguished" Europe from other civilizations (Gibbon, 1789, vol. 3, pp. 633–34).

[20] Even scholars of fundamentalist religious beliefs, such as the great Swiss Huguenot polymath Louis Bourguet (1678–1742), were able to develop what Barnett (2015, p. 149) has felicitously called a "strategy of toleration" in which deeply felt religious differences were papered over in scientific exchanges and a scholarly civility was maintained despite private outrage at the heretical opinions of "unbelievers."

[21] The term used in early modern Britain was "improvement" rather than progress. Slack (2015) traces the term "improvement" through seventeenth-century English culture and correctly observes that while economies and cultures move together, in this case cultural beliefs came first, because the "improving frame of mind" fostered the economic behavior that led to its realization (Slack, 2015, p. 4). See also Friedel (2007).

at times even misleading, yet without the formal knowledge they would not have emerged.[22] Second, notwithstanding the many disappointments and dead ends to which the application of science led, the most innovative and progressive entrepreneurs and industrialists of the age fervently held on to the cultural attitudes central to the Industrial Enlightenment.[23] The key to economic growth was useful knowledge, and its expansion and diffusion was therefore at the heart of institutions and policies that would bring about social progress.[24]

Third and most importantly, science mattered because it made the difference between an Industrial Revolution that was a minor and ephemeral blip in technological progress that eventually petered out into a new stationary state, and one that led to the continuous and cumulative growth we see after 1815, when formal knowledge increasingly found new ways to affect technology. After elementary modern chemistry emerged in the closing decades of the eighteenth century, thermodynamics, organic chemistry, and electricity followed in the first half of the nineteenth century, and metallurgy a few decades later — to name just a few.

25.4 Aptitudes

To make a difference in economic performance, the insights of natural philosophers and practical mathematicians had to be implemented. Ingenious devices should not only work, but be within range of the workmanship and materials of the age, so they could be scaled up and used widely. The brilliant sketches made by Leonardo Da Vinci in the late fifteenth century were never turned into working models, in large part because the workmanship and materials needed to produce them in quantities at reasonable cost were not available. The famous submarine built by the Dutch engineer Cornelis Drebbel in the 1620s and the calculating machine designed by Blaise Pascal in 1642 did not take off for similar reasons. Yet if breakthroughs in useful knowledge were to result in economic progress, they had to be transformed from blueprints into models, be tolerably free from breakdowns, and capable of being repaired by local mechanics. In the process of being implemented, the newly-invented techniques normally had to be tweaked, debugged, and adapted. To do so required, above all, technical competence, that is, highly skilled artisans working with good tools (made by other skilled artisans). What

22 Formal knowledge contains not just abstract and theoretical science but also experimental work, applied mathematics, and systematic data-collection. Progress in useful knowledge depended on insights generated by experimental scientists and well-educated engineer-savants such as John Theophile Desaguliers, René Réaumur, Joseph Black, Joseph Priestley, Charles Augustin Coulomb, Claude Berthollet, and Humphry Davy. Such people moved seemingly effortlessly between what McKendrick (1973, p. 313) has called the various "gradations of scientific knowledge and expertise" and the spread and adoption of experimental methods, mathematical practice, and the culture of open science.

23 James Watt wrote in 1790 (of himself in the third person) "These Gentlemen [Boulton & Watt] owe much of their success to the accurate philosophy of the last age, to the enterprising spirit of the present age, to the opulence of this country & to the decline of prejudice & attachment to ancient [candour?]. Had they lived in another age or in some other country, they might have been mere theorists or have rubbed through life unknowing & unknown unless they had happened to turn their abilities to the contrivance of instruments for the destruction of the human species?" Cited by Miller, 2009, p. 41.

24 The belief in the ability of science to aid production is supported by the many scientists who were hired as consultants by progressive farmers and manufacturers, foremost among them the Scottish physician and chemist William Cullen, the physicist and philosopher Joseph Priestley, and the practical mathematician and politician Davies Gilbert. For more details see Mokyr (2009), p. 58.

made the difference whether new technological ideas could actually have economic effects, more than most economists would assess, was the human capital and dexterity of the shopfloor workers using the devices.

In 1500 it would have been hard to observe that Europe's artisans were in any sense more skilled than those of India or China. Europeans sent their ships across the oceans to buy goods made by skilled Asian artisans, such as Indian cottons, Persian rugs, and Chinese porcelain. In many areas, European technology was still backward, though not quite as backward as it had been in 1000 AD. After 1500 things started to change. Two centuries later European had seen and described objects too small or too remote to be ever observed by human eyes, proved the shape and dynamics of the solar system beyond any reasonable doubt, manufactured objects that measured the time accurately and built musical instruments that played perfectly. By 1750, moreover, European artisans had acquired the capabilities that within a century would flood the Indian market with cheap cotton goods and defeat the Chinese navy in the first Opium War. These same capabilities allowed them within the next decades to design the devices that allowed them to determine longitude at sea, to defeat gravity, to conquer smallpox, to refine wrought iron from pig iron, to utilize binary coding to weave patterns into fabrics, and to convert heat into work using ever-more efficient engines. No other civilization had managed to solve so many difficult practical problems in such a short time. The Great Enrichment and the Great Divergence evolved cheek-by-jowl.

For such a history-changing phenomenon to occur, artisanal skills mattered. Scholars such as Epstein (2013) or Berg (2007) have indeed argued for the pre-eminence of the role of tacit skills that artisans possessed and transmitted through instruction and imitation. Relying on scattered evidence, Epstein (2008, p. 71) has suggested considerable productivity growth due to the anonymous improvements and experimentation carried out by Europe's craftsmen, from the woolen industry to printing and clockmaking. Whether technological progress occurred thanks to the benevolent actions of the guilds (as Epstein insists) or in spite of them, as Sheilagh Ogilvie (2014, 2019) has argued, is immaterial here. What matters is that such technological progress did occur in early modern Europe and that its artisans without any question were getting better. A perfect example of this continuous improvement is provided by Kelly and Ó Gráda (2017). In the seventeenth century, the English watch industry experienced a major technological shock by the invention of the spiral-spring balance in watches. No such discrete macro-invention occurred over the subsequent century, yet the real price of watches fell by an average of 1.3 percent a year between 1685 and 1810 (Kelly and Ó Gráda, 2017), the result of an increasingly finer division of labor and learning by doing. Another example is in the small arms industry. Hoffman (2015) shows the secular decline in the prices of firearms due to the growth in total factor productivity. He estimates a rise in total factor productivity of pistols at 1.1 percent a year (1556–1706) relative to a low-tech product such as spades. This, as he points out, is an underestimate since it does not account for quality improvements in muskets and pistols.

Epstein and his followers have argued that such cumulative incremental tweaks and improvements introduced by artisans alone might have been enough to sustain technological progress for a long time. Epstein dismissed the economic significance of codified formal knowledge that was generated and distributed by the Republic of Letters as inconsequential. By stressing the role of artisans, these scholars highlight a crucial component of the Great Enrichment but may have missed the profound complementarity between tacit skills and natural philosophy. Adam Smith expressed this when he noted that "to think or to reason comes to be, like every other employment, a particular business, which is carried on by very few people who furnish the public with all the thought and reason possessed by the vast multitudes that labour." The benefits of the "speculations of the philosopher ... may evidently descend to the meanest of people" if they led to improvements in the mechanical arts (Smith, [1776] 1976, pp. 569–72). Smith's "speculations" were strongly complementary to the kind of practical skills that could actually produce the goods in the workshops in which Europe's skilled artisans worked.

When this process of improvement in artisanal competence actually started is not easy to pin down precisely, and the timing surely differed from industry to industry and location to location. Many years ago Edgar Zilsel (1942) pointed out that artisans and craftsmen before 1600 were the "real pioneers of empirical observations, experimentation and causal research" (Zilsel, 1942, p. 551). Skilled craftsmen thrived in Elizabethan London and a few of them actually committed their practical knowledge to writing, such as Sir Hugh Plat (1552–1608), the author of many practical books full of recipes and prescriptions on a range of topics, from meat preservation and pest control to gardening (Harkness, 2007). In Germany, Augsburg and Nuremberg were renowned for their extremely skilled blacksmiths, with expertise in lock-making, sheet metalworking, etching, hammered inlay, steel-plate engraving, painting, and rustproofing. While German artisanal leadership experienced a major set-back during the thirty-years war, skills continued to advance elsewhere in Europe.

In Meisenzahl and Mokyr (2012), we distinguish between three levels of technological activity that drove innovation in this period. One entails the major breakthroughs (macroinventions) that solved a bottleneck or opened a new door. These were, by and large, the ones that made it into high school history books, making top of the line inventors engineers such as James Watt, John Harrison, and Samuel Crompton famous. Others in the top level contributed major improvements, and their names still appear in standard economic history texts, such as Richard Trevithick, Matthew Murray, and Henry Maudslay. However, the second level was what made their breakthroughs practical and economically significant. These were the myriad of small and medium-sized cumulative microinventions that improved and debugged existing inventions, scaled them up, adapted them to new uses, and combined them in new applications. The people behind these advances, the "tweakers," are harder to find in the historical record, because they improved and debugged *existing* inventions and thus appear in the shadow of the great inventors. Examples of those whose work has survived for posterity are Josias C. Gamble (1775–1848), an Irishman trained in Glasgow, who was essential to James Muspratt's introduction of the Leblanc process in Britain (Musson and Robinson, 1969, p. 187); William Horrocks of Stockport whose 1803 patent improved upon Cartwright's powerloom (Marsden, 1895, pp. 70–72); and William Woollat, who was Jedediah Strutt's brother in law and helped him develop a mechanized stocking frame that could make ribbed hosiery (Fitton and Wadsworth, 1958, p. 24).

The third level of activity, and perhaps the least recognized of Britain's advantages, were brought about by the thousands of skilled workmen capable of building, installing, operating, and maintaining new and complex equipment. The skills needed for these pure implementers were substantial, but they did not have to be creative themselves. It goes without saying that the line between tweakers and implementers is blurry, but at the very least a patent or some prize for innovation would be a clear signal of original creativity.

The high quality of craftsmanship in the eighteenth century was particularly notable in Britain, and it is thus not surprising that it was in that country that the inventions that created the Industrial Revolution, whether local inventions or ideas imported from the Continent, were first carried out on a massive scale (Kelly et al., 2014; 2020), even though Britain never accounted for even half of all the major inventions in that period. Contemporaries on both sides of the channel knew this all too well.[25] But the evidence is more than just contemporary opinion. As Henderson (1954) has shown in great detail, British engineers and mechanics swarmed all over the Continent, installing, operating, and maintaining equipment. Much of this knowledge was what we could call "tacit knowledge."[26]

One good example of a person embodying the kind of aptitude that made the British Industrial Revolution possible was John Whitehurst, a Derbyshire clockmaker and hydraulic engineer who also made important contributions to geology. A member of the Birmingham Lunar Society as well as the Royal Society, his consultant services were widely sought. While a contemporary wrote of him condescendingly as "an ingenious mechanic and worthy man but possessed of very little science" (cited by Vaughan, 2004), he was clearly the kind of top-of-the-line engineer that in Britain, perhaps more than anywhere else, was widely respected. Patronage was the result. Whitehurst was appointed in 1775 to the newly established office of stamper of money weights to the mint. The careers of men like Whitehurst, Smeaton, Watt, Rennie, Telford, and many others show the high social prestige associated with engineering skills and mechanical aptitude during the Industrial Revolution. Recent research (Hanlon, 2020) has stressed the key role that people who called themselves "engineers" played in the British Industrial Revolution.

Such people were not unique to Britain, even if Britain had a far larger that proportional share of them. The French instrument and clockmaker Jacques de Vaucanson was appointed inspector of the French silk industry and a member of the French *académie des sciences*. A striking example of the kind of high quality craftsmen in France who personified the cooperation between artisans and scientists is provided by Hilaire-Pérez (2007). She sees artisans not just as skilled but as incorporating a great deal of knowledge even if it was not, strictu sensu, scientific "in order to contrive new products and processes."[27] Paola Bertucci (2017) speaks of a French "Artisanal Enlightenment" driven by a group she calls *artistes*, somewhat vaguely defined as artisans with *esprit*. A small elite of skilled, creative, and well-trained workmen, the *crème de la crème* of French workmen, they included watchmakers, enamelers, instrument makers, high-end furniture makers and other high-skill artisans. *Artistes* were thus a middle category, wedged between uneducated artisans and intellectuals. More than most of the top echelons of Britain's mechanics, these people were literate who read Bacon and Descartes and some wrote books and articles on their crafts.

The class of elite artisans in France was different from Britain's. France was missing something that Britain had in large quantities, namely the very skilled but unpretentious down-to-earth practical mechanics slaving away in the grimy workshops of Leeds and Keighley (Cookson, 2018). French mechanics catered to the fashions and whims of the rich and glamorous rather than the needs of the masses. The French Enlightenment — including the Industrial Enlightenment — was first and foremost a social elite project, and its top artisans reflected this, worrying about elegance and taste more than

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25 One French writer in the mid 1780s feared much of the short-lived free trade between Britain and France and sighed that "We have set the French workmen to grips with the English workman. It is the combat of a naked man against an armed man and it has the outcome we may expect and the victory cannot be disputed. Is no resource left to us?" Cited by Harris (1998, p. 412). For other examples of contemporaries pointing to British superiority in technical competence, see Mokyr (2009, pp. 108–110).

26 Harris (1992), p. 33 referred to these skills as "unanalyzable pieces of expertise" and "the knacks of the trade."

27 Hilaire-Pérez (2007) cites the example of the French artisan Edmé Régnier (1751–1825), apprenticed as a gunmaker, whose talents as a craftsman allowed him to enter the circles of intellectuals, where he met such scientific celebrities as the Comte de Buffon and the physicist Charles-Augustin de Coulomb. His dynamometer designed to measure muscular strength was in Hilaire-Pérez's words, "an essential mechanism as quantification of labour became the cornerstone of engineering sciences" (p. 139).

price and cost. In France, the politics of class and status got often in the way of progress. British engineers (unlike their French colleagues) had few political ambitions or intellectual pretensions, rarely wrote books and chose to solve practical problems that would make money rather than earn them the approval of their social superiors.[28]

25.5 Apprenticeship and human capital

It is no secret where technical aptitude came from before and during the Industrial Revolution. As formal structured training in technical schools was practically non-existent, skilled artisans were trained in formal or informal apprenticeship relations with existing masters. Europe's master artisans thus produced two different outputs: material goods and technical training for the next generation. The process of intergenerational transmission of such tacit knowledge can become highly rigid and conservative, so that each generation reproduces accurately the knowledge of the previous one, or it can be flexible and open so that innovations are introduced, passed on, and become widely used, increasing average skill level and thus productivity.

How and why was the apprenticeship system in Europe different from the rest of the world? The key to the preservation and transmission of these tacit skills and there was the institutions that regulated apprenticeship. The need for such institutions is obvious once it is realized that the contract between master and apprentice is a highly asymmetrical one, riven with opportunities (for both sides) to cheat, shirk, or engage in other forms of opportunistic behavior (De la Croix et al., 2018; Mokyr, 2019). Without some institutional arrangement that would supervise and enforce the contract and resolve disputes, the system could well unravel. The nature of these institutions varied, but they helped determine the quality of the craftsmen.

How and why was the apprenticeship system in Europe different from the rest of the world? The key to the preservation and transmission of these tacit skills and their evolution depended on the institutions that regulated apprenticeship. The need for such institutions is obvious once it is realized that the contract between master and apprentice is a highly asymmetrical one, riven with opportunities (for both sides) to cheat, shirk, or engage in other forms of opportunistic behavior (De la Croix et al., 2018; Mokyr, 2019). Without some institutional arrangement that would supervise and enforce the contract and resolve disputes, the system could well unravel. The nature of these institutions varied, but they helped determine the quality of the craftsmen.

Two basic characteristics of the apprenticeship in Europe made the difference. One was that European apprentices could choose over a wider range of masters as they were not confined to members of their extended family. Family connections still mattered, but they did matter far less than elsewhere. European society was organized since medieval times by nuclear families, and every young lad looking to learn a trade from a master could pick a high quality one (if he could afford the fee) — hence minor innovations that improved the craftsman's skills and raised the quality and efficiency of production spread faster (De la Croix et al., 2018). It stands to reason that the most productive and sophisticated

[28] Bertucci rightly points out the differences between the French and British Societies of Arts: the British one (founded in 1754) encouraged artisanal creativity and did not seek state support (Howes, 2020). The difference was symbolic and underlines the different national styles of Enlightenment.

masters would attract the most apprentices, unless guild regulations prohibited them. The second feature of apprenticeship in much of Europe was mobility. Apprentices upon completion of their training moved about and learned from craftsmen other than their main master (or these learned from them) through the institution of journeymen (Lis et al., 1994; Belfanti, 2004). In that way, best-practice artisanal knowledge circulated in early modern Europe and led to the adoption of more efficient techniques and the slow but relentless improvement of skills.

As noted above, there is no reason to think that by the time Europeans reached Asia the European artisans were on average more skilled than their colleagues in India, China, or Japan. Yet by 1600 there are signs of an opening gap in some areas: Europe was pulling ahead in basic mechanical technology: screws, levers, pulleys, as well as optical instruments, printing, hydraulic technology, and precision mechanisms such as clocks, watches, toys, musical instruments, and guns. They were still behind in high-end textiles and ceramics, but by the eighteenth century those gaps were closed as Europeans built large mechanical silk-throwing plants and learned to spin high quality fine cotton yard, and print the fabrics in vivid colors. The aptitude of a highly skilled artisan such as Thomas Newcomen, who built the first working steam engine in 1712, was enhanced by the highly skilled workmen in the midlands.[29] The kind of continuous labor productivity growth mentioned earlier in firearms and watches also led to hard-to-observe but equally important improvements in quality, both of consumer goods and the tools available to artisans.

The separation I proposed between "propositional knowledge" and "prescriptive knowledge" (Mokyr, 2002) is an epistemic one — not a strictly social one. In early modern Europe, as well as during the period of the Industrial Revolution, the distinction between "knowers" (*savants*) and "producers" (*fabricants*) was hazier than sharp categories will allow for. Many artisans such as the sixteenth-century French potter Bernard Palissy were learned and sophisticated.[30] Leading natural philosophers were also skilled tool- and clockmakers, none more so than the great Robert Hooke and his contemporary, the Dutch mathematician Christiaan Huygens. As Edward Zilsel (1942) was one of the first to insist, early modern natural philosophers realized that the practical world of artisans was crucially important if material progress was to be achieved. The French philosopher Pierre de la Ramée wrote proudly that he had visited every mechanical workshop in Paris more than once and advised other philosophers to do the same (Hooykaas, 1972, pp. 99–100).[31] Paracelsus regarded artisans as the kind of practitioners who were in direct contact with nature, and who could be trusted more than natural philosophers because they relied on experience rather than on reasoning (Smith, 2006, pp. 298–299). Newcomen was

[29] When Newcomen came to the Midlands to install his steam-powered engine, he and his assistant were "at a loss about pumps, but being near Birmingham and having the assistance of so many ingenious and admirable workmen, they soon came to methods of making the pump-valves, clacks, and buckets" (Desaguliers, 1734–44, Vol. 2, p. 533).

[30] Palissy proudly conceded that he was a modest potter ignorant of classical languages, but would openly challenge the theories of the ancient and modern physicians, alchemists, and philosophers (Deming, 2005, p. 971).

[31] Indeed, some scholars (e.g. Roberts and Schaffer, 2007) have gone so far as to deny altogether a meaningful separation between science and technology at this time, and have proposed new concepts such as the "mindful hand"— educated and informed craftsmen. The notion that there was no meaningful between theory and practice seems far-fetched, but there were many skilled and trained people who were in the gray area that straddled both. Among those we should think of "practical mathematicians" — surveyors, map makers, optical instrument makers, and such. As Kelly and Ó Gráda (2020) note, "these practitioners spanned a continuous spectrum from anonymous artisans and schoolmasters to figures now usually thought of as scientists and mathematicians but whom their contemporaries saw equally as teachers, instrument makers, and engineers: Jost Burgi, Johannes Regiomontanus, Peter Apian, Gemma Frisius, Gerard Mercator and, most notably, Simon Stevin and Galileo."

described in the phrase of a recent author as "the first (or very nearly) and clearly the most important member of a tribe of a very particular, and historically original, type: the English artisan-engineer-entrepreneur" (Rosen, 2010, p. 40). We now know for certain that Newcomen, though by all signs lacking in formal education, had access to the kind of basic knowledge he needed in order to recognize why his engine would work (Wootton, 2015, pp. 499–508).

In the age of Enlightenment, the Baconian notion of building communication channels between natural philosophers and artisans became a dominant theme, a perfect example of an idea gaining acceptance in the market for ideas. Many of the institutions of public science such as scientific societies and academies were aimed at the demonstrations of the miracles that science could accomplish (Stewart, 1992). In private gatherings, in coffeehouses, inns, and domestic residences, scientists and artisans met one another and exchanged ideas. Many of the leading inventors of the eighteenth century had close connections with scientists. Some of them, of course, were able to straddle theory and practice, none perhaps more so than John T. Desaguliers (1683–1744), one of Newton's protegés and a devoted acolyte of the master. Desaguliers, who in many ways embodied the Industrial Enlightenment, was a tireless experimenter and practical instrument maker. In collaboration with the instrument and pump maker William Vream, he worked on the ventilation and heating issues, and redesigned chimneys and air heaters. He designed new types of water wheels and steam engines and constructed improved versions of various instruments, including a pyrometer, a barometer, a crane, and various pumps (Fara, 2004; Carpenter, 2011).

There were many dexterous and competent mechanics and engineers during the British Industrial Revolution with little formal knowledge, none more so than the prodigiously gifted craftsman Richard Roberts, most famous for the automatic or "self-acting" mule in 1825. Many others were ingenious craftsmen without much former education, such as Henry Cort, the inventor of the pathbreaking puddling and rolling process.[32] The great engineers John Rennie, James Watt, and John Smeaton straddled the worlds we would regard as science and those that we would see as technology. Relatively poorly educated but ingenious artisans such as George Stephenson, Roberts, and Cort found it necessary and were able to consult people more formally educated than themselves. There were institutions, mostly of the informal and private-order type, that supported these connections.[33]

To implement radical new designs, make them work and scale them up required skilled mechanics and technicians, especially ironmasters, woodworkers, engineers, and instrument makers. Without these skilled workers, the great inventions would have remained unfulfilled promises. Perhaps the most famous of these mechanics and ironmasters was John Wilkinson, whose Bradley works pioneered new boring machines that were able to produce the cylinders Boulton and Watt needed for their engines with unrivaled accuracy. But many others could be mentioned: Charles Gascoigne, who took over the failing Carron ironworks in Falkirk (Scotland) in the 1760s and rescued it through relentless improvement and the design of new and effective naval artillery, and Bryan Donkin, famous for his improvements to the mechanized papermaking machine, who was also the inventor of the tachometer, a steel nib pen, and the metal tin for canned food. Millwrights played a special role (Mokyr et al., 2020). Writing retro-

[32] Cort was "a plain Englishman, without Science" whose discovery was due to "a dint of natural ingenuity and a turn for experiment" as the scientist Joseph Black wrote to James Watt (cited by Coleman and MacLeod, 1986, p. 603).

[33] Richard Roberts, who had a very poor education, joined the Manchester Literary and Philosophical Society in 1823, contributed to their proceedings, and in 1861 was made an honorary member. This connection allowed him to rub shoulders with such scientific luminaries as Robert Owen, John Dalton, and James Prescott Joule.

spectively in the 1860s, the Scottish engineer William Fairbairn wrote that "The millwright of former days was to a great extent the sole representative of mechanical art ... a kind of jack of all trades who could with equal facility work at a lathe, the anvil, or the carpenter's bench... a fair arithmetician who could calculate the velocities, strength and power of machines..." (Fairbairn, 1871, p. ix–x).

Because of the importance of ingenuity and dexterity, the mechanical engineering and machine tool industry was an unheralded hero of the Industrial Revolution (Musson, 1975, 1980). It was led by some of the most gifted craftsmen of the Industrial Revolution such as Joseph Bramah and Henry Maudslay (MacLeod and Nuvolari, 2009). The role of the machine tool industry was emphasized by Nathan Rosenberg (1976, p. 19) who pointed out that "the machine tool industry may be looked upon as constituting a pool or reservoir of skills and technical knowledge which are employed throughout the entire machine-using sectors of the economy." Between 1780/89 and 1840/49 the percentage of patents in the English mechanical engineering sector increased from 17.8 to 28.6 (MacLeod and Nuvolari, 2009, p. 224). A substantial number of those were taken out by engineers (Hanlon, 2020).

James Watt, of course, personifies everything that one could mean by "aptitude," and justly became a national hero (MacLeod, 2007). An instrument-maker, not formally trained in the sciences, he relied on the advice of some of Scotland's best scientists, Glasgow University's Joseph Black and Edinburgh's John Robison. The specialists concluded that "one can only say that Black gave, Robison gave, and Watt received" (Dickinson and Jenkins, [1927] 1969, p. 16). Next to Watt himself stood the greatest civil engineer of the period, John Smeaton. Unlike Watt, Smeaton never made a spectacular breakthrough that would enshrine his name in high school textbooks, yet his career contained all the ingredients of what made the British Industrial Revolution work. Originally trained as a lawyer and an empiricist par excellence, he made sure to inform himself of pertinent scientific developments of his age.[34] In every way the embodiment of the Industrial Enlightenment, Smeaton recognized the importance of networks in creating and diffusing new useful knowledge and founded a society of engineers in 1771, eventually named after him.

Technical skills of the third level were especially useful in the constructing and maintenance of modern equipment. They could be found over Britain, but were concentrated especially in areas close to coal mines and textiles (Kelly et al., 2020). Cookson (2018, 154–155) points out that "there was a limit to how many James Watts could be accommodated in a business" and that the real need was for "skilled workers with shopfloor duties." Her book on the Yorkshire machinery industry contains a detailed survey of the competence and creativity of Yorkshire's ingenious mechanics. Trained in such skilled occupations as clockmakers, millwrights, or whitesmiths, many of these Yorkshire artisans worked in small workshops, often family affairs, aided by apprentices, journeymen and a few skilled assistants. It is striking how agile they were. As Cookson notes repeatedly, not only were they dexterous and well-trained, but their skills were sufficiently flexible to help them adapt to a changing economic and technological environment and continuous changes in the demand for skilled labor.

These workers were a crucial component of upper-tail human capital in an age when mechanical skills were what counted for technological progress. It was not formal education or literacy that were the engine of progress during the Industrial Revolution, but mechanical aptitude and competence. These

[34] Smeaton's contributions ranged across many fields: harbor engineering, bridge construction, water mills, the chemistry of cement, steam engines, canals, and lighthouses. Yet Smeaton was very much a loyal citizen of the Republic of Letters. He traveled to the Low Countries to study their canal and harbor systems, and taught himself French to be able to read the theoretical papers of French hydraulic theorists despite his conviction that all theoretical predictions had to be tested empirically.

skills helped Britain construct and improve the machinery and equipment that we associate with the Industrial Revolution. For Britain, and to a lesser degree for the rest of Europe, artisanal aptitude was an indispensable factor in the Great Enrichment.

25.6 Conclusion

Attitudes (that is, cultural beliefs) and aptitudes (that is, technical competence) thus played central roles in the British Industrial Revolution and the origins of modern growth. One might ask if we could see these as necessary or sufficient conditions. The answer depends a bit on whether we try to explain a few isolated macroinventions in the cotton and iron industry that some scholars see as the essence of the Industrial Revolution, or whether we are trying to explain the sustained advance on an ever-broader technological front in the nineteenth century as well It is hard to see how a few inspired inventions by skilled artisans in the mid eighteenth century could have converted the economic trajectory of much of the western world into one of sustained progress without the ever-growing infusion of formal codified knowledge created by natural philosophers, physicians, mathematicians, and chemists, among others into the body of useful knowledge. At the same time, however, formal theoretical knowledge, no matter how sophisticated, depended on dexterous practical artisans to become economically significant. Both of these depended in turn on underlying institutions, often designed for very different purposes.

Modern economic growth, then, needed *both* attitude and aptitude as necessary conditions. Yet even together, a belief in progress-through-knowledge and the technical skills to turn them into a reality would not have been sufficient without the proper institutions in place. There was a deep complementarity and synergy between technological and institutional change (Mokyr, 2006, 2008; Hoffman, 2020). Advances in useful knowledge that were unaccompanied by institutional change could fizzle out. If institutions were not aligned to support an economically productive research agenda, the growth in useful knowledge might have continued apace, but be diverted into welfare-neutral or welfare-reducing directions, such as numerology, astrology, or more destructive weaponry.[35] More likely, however, technological progress would have slowed down and eventually ceased altogether much as happened in Ming-Qing China. Institutions needed to be in place to encourage, incentivize, and protect successful intellectual innovators. Intellectual and technological innovation might eventually end up being increasingly resisted by intellectual ancestor worship, an entrenched incumbent scientific paradigm, or by workers who felt that their livelihood was threatened by new techniques. If that resistance had not been overcome, technological progress might have been extinguished. It is thanks to the European Enlightenment that institutional change after 1750 became more or less aligned with the needs of a dynamic economy. Yet the institutional transformation was incomplete, and neither economic nationalism nor pervasive rent-seeking were extinguished. Unless institutional changes can be continuously aligned with technological progress, the road to sustained prosperity will remain hazardous. In our time, despite ever-accelerating technological progress and with the decline in civil society and the weakening of open and free economies, this seems less promising than in 1850.

[35] For more detailed surveys of the role of institutions in the Industrial Revolution see Mokyr (2008), Kapás (2012), and Hoffman (2020). For a critical view, see McCloskey (2010), pp. 296–346.

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