# The Market for Ideas and the Great Enrichment

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**Introduction**

The term “Great Enrichment” proposed by McCloskey (2016, p. 5) strikes me 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), since the latter is a statement about *relative* income between the West and the Rest, whereas “enrichment” points to the world-wide increase in every measure of living standards than one can think of. What counts is material improvement, which is what economics is all about. The gap that opened up after 1800 between rich and poor countries is of course a major issue in global history, and has had profound implications. 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 gap is still as gaping as ever. Yet if poverty is now declining world-wide, the “deep” reason is the growth of what Europeans called “the useful arts” or “useful knowledge.”

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. State actions, often driven by mercantile political influence led to the forceful seizure of Atlantic markets by British and French agencies, writes Prasannan Parthasarthi (2011, p. 143), and the technological progress that occurred was the outcome of an “explicit rejection of market outcomes” (ibid., p. 62). Anievas and Nisancioglu (2015) 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 industrialisation, further assisting its global supremacy. They 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" (pp. 121-122). Equally explicit is Sven Beckert's much-praised volume on 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 basic changes in Europe that made it possible. Nobody will deny the salient facts of European 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 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 is still based on an implicit zero-sum image of the world. In economic history, zero sum games are exceedingly rare. Violence, conquest, and exploitation are negative sum, trade and technological progress are positive sum.

Much more plausible to cool-headed observers 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, which 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 in 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).

Yet a causality 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 and allowed them to subjugate non-Europeans, from Peru to the Gold Coast to Java? It just cannot stand up to scrutiny to assert, as does Parthasarathi, that as late as 1750 Europe and India were at comparable levels of development. This is not to deny the sophisticated skills of Indian (and Chinese) artisans, which made their products so highly desirable in Europe. 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 and 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 this question is not unanswerable; by 1750, surely, Europeans knew more than non-Europeans about subjects that affected or would soon affect living standards. We can actually make some progress as to why this might have been the case. The summary of the explanation is differences not in "wisdom," as Johnson's philosopher surmised, but in *attitude* and *aptitude*, that is cultural beliefs and technical competence. Both of these were the result, and in turn causal of, differences in institutions.

**Attitudes.**

One of the most striking phenomena in cultural beliefs is the widespread persuasion that earlier generations, for some reason, were wiser that the present. 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, 112, see www.yeshiva.org. il/wiki /index.php?title= "chazal's authority in the determination of the halacha"). This was not, in its basic outlook, inherently different from the attitudes to 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). This veneration for ancient knowledge has 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. 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).

One of the most dramatic developments in Europe's cultural life after 1500 was the slow but inexorable melting away of this inferiority complex. In the late Middle Ages a powerful orthodoxy had been established that merged Christianity with Aristotelian philosophy and classical science, the monumental life work of Thomas Aquinas. Yet after 1450, small cracks in this structure started to emerge, and in the next centuries it showed serious signs of weakening. 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).

By the late seventeenth century, at the dawn of the Enlightenment, European intellectual commitment to the science of the ancients was largely gone. The slogan of the Royal Society, *nullius in verba* (on nobody's word) could well have been applied to the totality 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.

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 new world view on known facts and theory, Galileo was able to prove him right through his ability to discern the phases of Venus. 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. By the end of the seventeenth century, Francesco Redi showed that spontaneous generation was fallacious as well. From Paracelsus to Andreas Vesalius and William Gilbert, early-modern European scientists felt free to criticize classical science and suggest 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 things that the ancients could not.

Yet all those 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 on the one hand, and could not be effectively suppressed by conservatives and vested interests on the other. A new set of institutions encouraged out-of-the-box thinking. Like every market, the market for ideas needed an institutional foundation that set 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 derived primarily from patronage that was offered to the most successful intellectual innovators. Success was measured by reputation — mostly created by peers who were in the best position to evaluate scientific work (Dasgupta and David, 1994). Reputation 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. But such patronage could also be found in the courts of the nobility and royalty. Some of those court 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 great astronomers Brahe and Kepler, but also scholars like Carolus Clusius, né Charles de l'Écluse (1526–1609). Clusius, one of the founders of modern botany, was learned, cosmopolitan, widely traveled, well-connected, he worked for both Rudolf II and Rudolf's father Maximilian II (Evans, 1973, pp. 119–20). 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 to a reasonable degree of accuracy. Many lesser rulers and wealthy nobles similarly extended patronage to leading scholars.

The demand for scholars had also pragmatic aspects. Many of the most successful scholars 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: Galileo, while still working in Padua, freelanced for the Venetian arsenal and invented a geometric and military compass (used for gunnery), as well as other militarily useful devices. Others were employed as tutors, most famously René Descartes at the court of Queen Christina of Sweden. 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. 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. In all of those cases, reputations — as established through publication and correspondence with peers — were decisive. The demand side was highly competitive. 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.

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. For scientists and artists to be recognized by figures of high social standing and power mattered 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 economic motives by scientists. Instead he argued that being associated with the mighty and rich elite 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, but the patronage transaction was clearly a complex exchange.

What made this market work, and what drove the culture and attitude of European intellectuals, was an underlying institution that set the rules of the scholarly game that were accepted by the vast majority of participants. This was not a formal, state-run institution but a virtual international network of scholars who shared interests and scholarly ambitions. Known to its members as the "Republic of Letters," it served as a clearinghouse for scholarly work written in Europe and thus created a mechanism to evaluate any kind of intellectual innovation. 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. 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). But it is only in a community that is both competitive and collaborative — such as is the case in a comparatively free market for ideas — that genuine progress was achieved and that the knowledge-foundation (or the epistemic base) of the techniques that drove the Great Enrichment was laid.

To be sure, not everyone who desired peer recognition did so for financial reasons. 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 exact 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.

In this competitive environment, the paralyzing respect for classical learning 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 exegesizing classical authorities to observations, experiments, and logic (including mathematics). Such transitions were very gradual, and even when ancient truths were overturned, it was often hard to abandon Aristotelian concepts. William Harvey, whose discovery of the circulation of the blood challenged fundamental physiological principles, 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. Scientists, in their eagerness to impress one another (and indirectly those who would extend patronage to them), criticized the conventional wisdom, and if they only could, shot it to pieces. Intellectual property rights assumed the form of priority: the first person to enunciate a new idea received theoretically the credit for the new idea and the reputation effects of that credit. The system, of course, did not work 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 one recent scholar has summarized, "priority disputes are an infallible indicator that knowledge has become public, progressive and discovery-oriented" (Wootton, 2015, p. 96). 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 around1665. According to an unsubstantiated account, De Graaf died as a result of the exhaustion caused by the priority dispute (Cobb, 2006, pp. 184-85).

Progress occurred, but the new interpretations did not invariably offer what we would judge to be improvements on existing knowledge: the iconoclasic 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, the phlogiston theory proposed by German scientists in the late seventeenth century revised Greek chemical theory by replacing the four elements by a new set, one of which was phlogiston that flowed out of a material when it burned. Yet the transformation of chemistry in the age before the Industrial Revolution is emblematic of how the competitive market for ideas worked. When the experimental work of Lavoisier and his students later in the eighteenth century showed unequivocally that phlogiston theory was erroneous and inadequate, it was discarded.

Europe's spectacular 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. Yet the success of its market for ideas in generating this progress was the result of neither design nor intent, but a classic "emergent property," the macro-level consequences of lower-level interactions. What made Europe the birthplace of the Great Enrichment was a unique set of circumstances. 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). Between 1500 and 1700 European polities were constantly fighting one another. To make things worse, the Reformation created another casus belli in Europe, and aggravated dynastic and colonial conflicts. The political fragmentation of Europe was enormous costly; some European wars were devastating, especially the French religious wars (1562-1598) and the Thirty Years war (1618-1648). Many prosperous regions were devastated, and roaming soldiers spread disease and destroyed both cities and countryside.

And yet the political fragmentation of Europe was indispensable for its intellectual development. The reactionary forces in Europe who were the natural allies of the vested interests defending the ancients 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. Not all Catholics were conservatives, and not all conservatives were Catholics. But iconoclastic intellectuals moved on the seams between polities and religions and were often virtuosos in playing the great powers against one another. Suppressing non-conformists became almost impossible, as many scholars found it easy to circumvent censors by publishing their work abroad, and when necessary could move across the border, where their international reputations often meant a warm welcome and a nice pension. As a result, despite some local victories, the moderns decisively won the battle.

While European intellectual life was thus benefitting from fragmentation, it was able to maintain a much needed unity. The Republic of Letters created an intellectual institution that was truly transnational and that ensured that every scholar catered to a continent-wide constituency. 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 apprehension of a single "great republic" guaranteed a "general state of happiness, system of arts and laws and manners." It "advantageously distinguished" Europe from other civilizations, he wrote (Gibbon, 1789, vol. 3, pp. 633–34).

The long-run benefits to the growth of knowledge were substantial. Above all, it undermined the centuries-old monopoly of the Church on the European market for ideas. By 1650 or so, intolerance was fading away and by the Age of Enlightenment persecution for heresy or apostasy had become little more than window-dressing in much of Europe. The market for ideas in Europe had become more free and more efficient that it had ever been before, and more so than anywhere else. And so it came to be that one of the great winners in this market was a belief in progress, not just economic progress but also social and political progress toward harmony and a better society. Much of the latter turned out to be illusory. The only one in which there can be little doubt that the improvement is real and demonstrable is economic growth. The attitudes and beliefs that prevailed in the early modern market for ideas created the historical phenomena that created the great Enrichment: the Scientific Revolution, the Enlightenment, and the Industrial Revolution.

**Aptitudes**

To make a difference in economic performance, the ideas of natural philosophers had to be implemented. The brilliant sketches made by Leonardo Da Vinci in the late fifteenth century were never carried out into working models, in large part because the workmanship and materials 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, and the models had to be scaled up, produced in large numbers, be tolerably free from breakdowns, and capable of being repaired. In the process, the newly-invented techniques normally had to be tweaked, debugged, and adapted. To do so required, above, technical competence, that is to say, highly skilled artisans. What made the difference whether new technological ideas can actually have economic effects is, more than most economists would assess, were the quality of workmanship, materials, and the understanding of the physical and biological regularities of the natural phenomena that technology harnessed for human needs.

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 Indian cottons, Persian rugs, and Chinese porcelain. In many areas, European technology was still backward, though probably not quite as backward as it had been in 1000 AD. Two centuries later European had seen and described objects too small and too remote to ever observe with human eyes, proved the shape of the solar system beond any reasonable doubt, and demonstrated that organisms did not arise spontaneously. 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 theme withing the next decades to design the devices that allowed them to measure longitude at sea, to defeat gravity, 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 had become the Great Divergence.

Artisanal skills mattered. Scholars such as Epstein (2013) or Berg (2007) have indeed argued for the pre-eminence of the kind of tacit skills that artisans possessed and transmitted through instruction and imitation. Epstein (2008, p. 71) has suggested considerable productivity growth due to the anonymous improvements and even experimentation within Europe's craftsmen, from the woolen industry to printing and clockmaking, though his evidence is scattered. Whether his evidence is thanks to the benevolent actions of the guilds (as Epstein insists) or occurred in spite of them, as Sheilagh Ogilvie (2014) 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 (2016), who show in the seventeenth century, the industry experienced a major technological shock by the invention of the spiral-spring balance in watches. No 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 a gradually finer division of labor and learning by doing.

Epstein and his followers have argued that such cumulative incremental tweaks and improvements introduced by artisans might have been enough to sustain technological progress for a long time. They dismiss the role of codified formal knowledge that was generated and distributed by the Republic of Letters as inconsequential. In so doing, they point to a crucial component of the Great Enrichment but may have missed the profound complementarity between tacit skills and codified 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] 1978, pp. 569–72). But Smith's "speculations" were strongly complementary to the kind of practical skills that could actually produce the goods in the artisanal workshops in which Europe's skilled artisans worked.

When this process actually started is very hard to pin down precisely, and 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 Meisenzahl and Mokyr (2012), we distinguish between three levels of technological activity that drove innovation in this period. One were the major breakthroughs (macroinventions) that solved a major bottleneck and opened a new door. These were, by and large, the ones that made it into economic history textbooks, making people like James Watt, John Harrison, and Samuel Crompton famous. Another was the myriad of small and medium cumulative microinventions that improved and debugged existing inventions, adapted them to new uses, and combined them in new applications. These 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 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). A third group, and perhaps the least recognized of Britain's advantages, was the existence of a substantial number 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.

It is no secret what created high quality craftsmen. As structured training in technical schools was non-existent, they were all trained in formal or (in a few cases) informal apprenticeship relations with existing masters. Europe's artisans all produced two different outputs: material goods and training for the next generation. The process of intergenerational transmission of such tacit knowledge can be 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 passed on and become widely used, increasing average skill level and thus productivity.

How and why was the apprenticeship system in Europe different? The key to the preservation and transmission of these skills, which remained largely tacit, was the institutions that regulated apprenticeship. Two basic characteristics of the apprenticeship in Europe made the difference. One was that, whether the contract between master was enforced by a craft guild, by the local government, or by reputation mechanisms, European apprentices could choose over a wider range of masters. Family connections mattered far less than elsewhere. Europe was organized by nuclear families, and every young lad looking to learn a trade from a master could pick a high quality one — hence minor innovations that improved the craftsman's skills and raised the quality and efficiency of production spread faster (De la Croix, Doepke and Mokyr, 2017). Moreover, in much of Europe many apprentices were mobile and moved about after the completion of their first training and learned from craftsmen other than their main master (or these learned from them) through the institution of journeymen (Lis, Soly, and Mitzman, 1994; Belfanti, 2004). In that way, artisanal knowledge circulated in early modern Europe and led to the slow but powerful improvement of skills.

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 were first carried out on a massive scale (Kelly, Mokyr, and Ó Gráda 2014) even though Britain never accounted for even half of all the major inventions in that period. Contemporaries knew this all too well: the French political economist Jean-Baptiste Say noted in 1803 that "the enormous wealth of Britain is less owing to her own advances in scientific acquirements, high as she ranks in that department, as to the wonderful practical skills of her adventurers [entrepreneurs] in the useful application of knowledge and the superiority of her workmen" (Say [1803], 1821, Vol. 1, pp. 32–33). As Henderson (1954) has shown in great detail, British engineers and mechanics swarmed all over the Continent, installing, operating, and maintaining equipment.

One good example of the kind of aptitude that made the Industrial Revolution possible was John Whitehurst, a Derbyshire clockmaker and hydraulic engineer whose consultant services were widely sought and who also made important contributions to geology. He was a member of the Birmingham Lunar Society as well as elected to the Royal Society. 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 admired. 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, Watt, Rennie, Telford, and many others shows the high social prestige associated with engineering skills and mechanical aptitude during the 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 as not just 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." She cites the example of the French gunmaker 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).

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 of the great scientists of the age were also brilliant instrument makers, none more so than the great Robert Hooke. But one could make the list endless long, including the sixteenth-century French potter Bernard Palissy and the seventeenth-century Dutch mathematician Christiaan Huygens. As Zilsel (1942) was one of the first to insist, early modern theorists realized that the practical world of artisans was crucially important if progress was to be achieved. 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). Indeed, some scholars (e.g. Roberts and Shaffer, 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. 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 (e.g. Smith, 2006, pp. 298-299). By the early eighteenth century the first person to build a working atmospheric engine, Dartmouth blacksmith Thomas Newcomen, was 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 uneducated, had access to the kind of basic knowledge he needed in order to realize why his engine would work (Wootton, 2015, pp. 499-508).

In the age of Enlightenment, the Baconian idea 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). But even in private gatherings, in coffeehouses and inns, scientists and artisans met one another. Many of the leading inventors of the eighteenth century had close connections with scientists, and many of the most progressive manufacturers employed scientists and professional engineers as consultants. Some of them, of course, were able to straddle both 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. Yet he 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).

Gifted mechanics and engineers in the British Industrial Revolution were many, none more so than the prodigiously gifted craftsman Richard Roberts, most famous for the automatic or "self-acting" mule in 1825, and the great engineers John Rennie, George Stephenson, and Richard Trevithick. Many of these people straddled the worlds we would regard as science and those that we would see as technology. Others, of course were simple if ingenious craftsmen without much former education, such as Henry Cort, the inventor of the pathbreaking puddling and rolling process. 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. Yet relatively poorly educated men such as George Stephenson, Roberts, and Cort found it necessary to consult people more formally educated than themselves. It is exactly by laying these connections that economic growth became a reality.

Radically new designs required skilled mechanics and technicians, especially ironmasters, woodworkers, engineers, and instrument makers, to be perfected and scaled-up. Without these skills, the great inventions of Watt, Murdock, Smeaton, and Hargreaves 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. Writing retrospectively 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).

The mechanical engineering and machine tool industry was an unheralded hero of the Industrial Revolution which depended primarily on ingenuity and dexterity. 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). Nobody stressed the role of the industry more emphatically than the late 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).

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 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. His 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. He founded a society of engineers in 1771, eventually named after him.

However, it was more than just engineering, machine tools, millwrights, and textiles. High skills that were especially useful in the constructing and maintenance of modern equipment were spread all over Britain, even if they comprised a small part of the labor force. They were precisely what is meant by upper-tail human capital. These were the competence and dexterity of instrument- and clock-makers, toy makers, iron masters, lens grinders, physicians, chemists, coal viewers, and shipwrights. These skills helped Britain construct and improve the machinery and equipment that we associate with the Industrial Revolution. Throughout Britain, and to a lesser degree the rest of Europe, artisanal aptitude was an indispensable factor in the Great Enrichment.

## Conclusion

Attitude (that is, cultural beliefs) and aptitude (that is, technical competence) played central roles in the European 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 inventions 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 a broad technological front in the nineteenth century as well. If the causes of the latter is the question posed, it is hard to see how a few inspired inventions by skilled artisans could have been converted into sustained progress without the ever-growing importance of formal codified knowledge. At the same time, however, formal theoretical knowledge, no matter how sophisticated, depended on dexterous practical artisans to turn their ideas into reality.

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). 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 may have continued apace, but be diverted into welfare-neutral or welfare-reducing directions, such as numerology, astrology, or more destructive weaponry.

As we have seen, institutions needed to be in place to incentivize successful intellectual innovators. Moreover, intellectual innovation might eventually end up being increasingly resisted by an entrenched incumbent scientific paradigm or technology; if that resistance had not been overcome, technological progress might have been extinguished. It is thanks to the European Enlightenment that institutional change was more or less aligned with the needs of a dynamic economy that required continuous progress. Yet the institutional change was incomplete, and neither economic nationalism nor pervasive rent-seeking were extinguished. Unless institutional improvements can be continuously aligned with technological progress, the road to sustained prosperity will remain hazardous.

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