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The European Enlightenment, the Industrial Revolution, and Modern Economic Growth

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*The European Enlightenment, the Industrial Revolution, and Modern Economic Growth**

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Introduction.

The issue of the emergence of modern economic growth in the nineteenth-century West has once again resumed its rightful place at the center of attention of a large group of scholars, coming from economics, history, and the other social sciences. While different approaches have been taken to understand the causes of the Great Divergence, they all share two fundamental assumptions. One is that modern economic growth started in the "West" — that is, selected economies in the northern Atlantic region. The other is that in this process Britain was a leader, while Continental Europe was a follower, if a rather quick one.

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This lecture is primarily about the former assumption. It argues that most of the countries that in 1914 belonged to the "convergence club" — countries that were industrialized, urbanized, educated, and rich — were countries that in the eighteenth century were subject to the European Enlightenment. This strong correlation is not in and of itself proof of causality, we need at the very least establish the mechanisms through which the Enlightenment affected the "real economy" and show that they mattered. In doing so, I will deal only with part of the story. The Enlightenment affected the economy through two mechanisms. One is the attitude toward technology and the role it should play in human affairs. The other has to do with institutions and the degree to which rent-seeking and redistribution should be tolerated. This is an interpretation of the Enlightenment that will surely not cover everything we know about it, but it may be what mattered most from the point of view of economic growth. The second set of problems, dealing with the impact of institutions, has been dealt with elsewhere and will not be the subject of this lecture (Mokyr, 2006a, 2007a; Mokyr and Nye, 2007).

Do beliefs and attitudes matter to economic outcomes? The debate goes back at least to Marx, who famously argued against it.[1] Keynes, on the other hand, went on record in his well-known last chapter of the *General Theory* arguing that ideas had the power to affect economic outcomes. In this debate, the answer the economic historian must give is that it all depends on the circumstances. But in the eighteenth century the circumstances were correct for changes in beliefs to affect economies as a whole. The Enlightenment changed the outlook of key persons on their natural environment, and their inventions and discoveries turned what might have become another technological efflorescence into a sea change in economic history.

The importance of the Enlightenment to the subsequent economic development of Western Europe is consistent with both the temporal and geographical pattern of growth. The economic transformation occurred at the end of the Enlightenment and after it, and it was entirely confined to nations that had been exposed to it, although timing patterns were variable. By 1914, the convergence club of industrialized and rich economies consisted almost entirely of countries that had been exposed to it two centuries earlier. Such correlations do not constitute proof. What is needed is to unpack the mechanism that created modern economic growth and link it to the intellectual developments that preceded it.

The Industrial Revolution and Modern Growth

The Industrial Revolution itself, in its classical definition, did not suffice to generate sustained economic growth. It is easy to imagine a counterfactual technological steady state of the techniques that had emerged between 1750 and 1800 of throstles, wrought iron, coke-smelting, and stationary steam engines, in which there was a one-off shift from wool to cotton, from animate power to low-efficiency steam engines and

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[1] "It is not the consciousness of men that determines their being, but, on the contrary, their social being that determines their consciousness" (1859, p. 4). This view is reflected in the thinking of current-day economists, who are as far from Marxism as can be. For instance, "Ideology may perhaps be considered a random shock in a model of institutional change, … but the absence of any positive theory of idea formation or role for ideology leads us to support economizing activity as the primary explanation for institutional change… Ideology may be usefully be thought of as a 'habit of mind' originated and propelled by relative costs and benefits. As an explanation for events or policies, it is a grin without a cat" (Ekelund and Tollison, 1997, pp. 17-18).

from expensive to plentiful wrought iron. It is easy to envisage the economies of the West settling into these techniques without taking them much further. Such a development would have paralleled the wave of inventions of the fifteenth century with the printing press, the three-masted ship, and iron-casting settling into dominant designs and the process of improvement subsequently slowing down to a trickle.

Why did this not happen? The fundamental reason is that before the Industrial Revolution all techniques in use were supported by very narrow epistemic bases. That is to say, the people who invented them did not have much of a clue as to why and how they worked.[2] The pre-1750 world produced, and produced well. It made many path-breaking inventions. But it was a world of engineering without mechanics, iron-making without metallurgy, farming without soil science, mining without geology, water-power without hydraulics, dye-making without organic chemistry, and medical practice without microbiology and immunology. The main point to keep in mind here is that such a lack of an epistemic base does not necessarily preclude the development of new techniques through trial and error and simple serendipity. But it makes the subsequent wave of micro-inventions that adapt and improve the technique and create the sustained productivity growth much slower and more costly. If one knows *why* some device works, it becomes easier to manipulate and debug it, to adapt to new uses and changing circumstances. Above all, one knows what will *not* work and thus reduce the costs of research and experimentation. The Industrial Revolution, in short, would have been eventually constrained by the narrowness of useful knowledge and ground to a stop.

And yet, a simple connection between the Scientific Revolution of the seventeenth century and the Industrial Revolution that followed it has proven remarkably elusive.[3] Scholars have found it difficult to link the main technological breakthroughs of the Industrial Revolution to the scientific discoveries of its time, although some notable exceptions to this rule can be pointed out. The solution consists of two components. One is simply a matter of timing: while the main advances during the first stage of the Industrial Revolution (say, 1760-1800) were only weakly based on science, its subsequent momentum increasingly came to depend on the better understanding of the propositional knowledge underlying the invention. The second is that the epistemic base of inventions does not only include a modern definition of science, but a broader definition of knowledge including simply catalogs of phenomena and regularities that could be relied upon even if the underlying processes were not quite understood. Thus tables of the efficiency of steam power were already formulated in the 1710s and widely used in the eighteenth century long before scientists formulated the laws of thermodynamics.[4] Lists and detailed descriptions of practices in fields as far apart as

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[2] I have developed this framework in some detail in Mokyr (2002) and (2005).

[3] The opus classicus arguing the case for such a connection remains Musson and Robinson, 1969. Critical of this approach are Mathias, 1979; McKendrick, 1973; and Hall, 1974. A more recent assessment is Cohen, 2004. For recent attempts to rescue the importance of the rise of modern science in the eighteenth century see Bekar, Carlow and Lipsey, 2006 and Jacob and Stewart, 2005.

[4] In 1718, Henry Beighton published a table entitled *A Calculation of the Power of the Fire (Newcomen's) engine shewing the Diameter of the Cylinder, for Steam of the Pump that is Capable of Raising any Quantity of Water, from 48 to 440 Hogsheads an Hours; 15 to 100 yards.* Beighton's Table was reproduced in Jean T. Desaguliers's widely read textbook, *Course of Experimental Philosophy*, p. 535. Desaguliers remarked that "Mr. Beighton's table agreed with all the experiments made ever since 1717."

farming, geology, and the performance of water mills helped engineers and producers improve their practices.

The centrality of technology in the emergence of modern economic growth is not really contested. Growth was possible through capital accumulation, increasing trade, better internal allocations, freer markets, and improved institutions. But all of those processes would eventually run into diminishing returns. It is technology that remains at the foundation of modern economic growth. Indeed, the various other definitions of the Industrial Revolution, such as a growing reliance on formal markets and a change in production organization toward the factory system were all endogenous to the changes in technology. A full explanation will need to deal with both the growth of useful knowledge and with the incentives and opportunities to take full advantage of it. Below I will cover only one aspect of it, namely the role played by the Enlightenment in generating this knowledge.

The European Enlightenment was a multifaceted phenomenon, much of it concerned with natural law and justice, religious and political tolerance, human rights and freedom, inequality, legal reform, and much else. At the deepest level, however, the common denominator was the belief in the possibility and desirability of human progress and perfectibility through reason and knowledge. Kant’s famous suggestion for the motto of the Enlightenment as “dare to know” is particularly apposite in this context. The material aspect of this belief followed in the footsteps of Francis Bacon's idea of understanding nature in order to control her and has been named in his honor the Baconian Program, although its parentage was of course far more complex than that. In the words of one scholar “The major purpose of Baconian natural philosophy is to produce innovations of which nature unaided is not capable” (Zagorin, 1998, p. 97). The program that Bacon suggested to attain material progress through technological progress consisted of the application of the inductive and experimental method to investigate nature, the creation of a universal natural history, and reorganization of science as a human activity (Gillespie, 1960, p. 78). Interestingly enough, Bacon has been heavily criticized by modern critics of industrial society. It is ironic that those who were born late enough to have benefited the most from advances inspired by his insights have heaped the most scorn on his “disastrously mistaken belief that nature and the creation are ordained for man’s benefit and rule” (Zagorin, 1998, p. 121). It is even more striking that those who regard the Industrial Revolution and the subsequent process of economic growth as fundamentally a positive development (that is to say, economic historians) have never given the Baconian Program much credit for this development. It is this omission that I hope to rectify below.

Useful knowledge became the buzzword of the eighteenth-century Enlightenment. The term should not be associated simply with either ’science’ or ’technology’.[5] It meant the combination of different kinds of knowledge supporting one another. The eighteenth century marked both an acceleration of the pace of research and a growing bias toward subject matter that, at least in principle, had some practical value. Indeed, Peter Burke

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[5] This point has been well-made by Inkster (2004), whose analysis parallels what follows in certain respects. Inkster proposes the term URK (’Useful and Reliable Knowledge’), which is much like the term proposed by Kuznets, who preferred ‘testable’. In my view *reliability* is an important characteristic of useful knowledge, but it seems less crucial than *tightness*, that is, the confidence and consensualness with which certain knowledge is held to be ‘true’.

(2000, p. 44) has argued that the eighteenth century saw the rise of ’the idea of research’ and the sense that this knowledge could contribute to economic and social reform, a notion directly attributable to Bacon. The change in the pace of progress of knowledge after 1680 was indebted to the influence of Bacon but equally to the triumph of Newtonianism in the first half of the eighteenth century. The achievement of Newton did more than anything else to establish the prestige of formal science in the world of learning (Jacob and Stewart, 2004).

The fundamental assumption of the Enlightenment, then, was that the growth of useful knowledge would sooner or later open the doors to prosperity. The belief was that the expansion of useful knowledge would solve technological problems and that the dissemination of existing knowledge to more and more people would have what we could call today substantial efficiency gains. These two notions formed the core of Denis Diderot’s beliefs and his admiration for Bacon permeates his writing as it does that of many other eighteenth-century *philosophes* and scientists. In Britain, of course, this belief was not only widespread, but formed the explicit motive for the foundation of organizations and societies that were designed to advance it, above all the Royal Society, and the Society of Arts.[6] It was the triumph of hope over experience.

Not all of it was abstract science: the taxonomic work of Linnaeus and the descriptive writings of Arthur Young increased useful knowledge just as much as the abstract mathematics of Laplace and the experiments of Priestley and Lavoisier. But it was also clear that this growth could only be carried out collectively, through a ’division of labor’ in which specialization and expertization were carried out at levels far higher than before, just as Bacon had foreseen in his *New Atlantis* in which Salomon’s House is a visualization of a modern research academy.[7] All the same, the way useful knowledge increased in the eighteenth century was a far cry from the processes of R&D (corporate and government) of today. It might be better to say that much of it was by way of exploration and discovery, trial-and-error processes minimally informed by an understanding of the natural processes at work, inspired tinkering, and a great deal of serendipity and good fortune, albeit favored by prepared and eager minds. Over the eighteenth century these research processes became more systematic, careful, and rigorous. By the early nineteenth century the interaction between knowledge “what” (propositional) and knowledge “how” (prescriptive) became much tighter. It is this phenomenon, more than anything else, that prevented the early Industrial Revolution from fizzling out and enabled it to become the taproot of modern growth.

The Enlightenment and Technological Progress

How, then, did the Enlightenment affect the nature of invention and innovation in the eighteenth century? The Enlightenment was an intellectual process and it was primarily about persuasion. The assumption was that society was improvable, and that a complete program of how to bring this about was worked out and needed to be

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[6] William Shipley’s credo is summed up in his “plan” for the establishment of the Society of Arts (1754): “Whereas the Riches, Honour, Strength and Prosperity of a Nation depend in a great Measure on Knowledge and Improvement of useful Arts, Manufactures, Etc... several [persons], being fully sensible that due Encouragements and Rewards are greatly conducive to excite a Spirit of Emulation and Industry have resolved to form [the Society of Arts] for such Productions, Inventions or Improvements as shall tend to the employing of the Poor and the Increase of Trade.” (Allan, 1979, p. 192).

[7] Priestley, 1768, p. 7. Adam Smith, in the ‘Early Draft’ to his *Wealth of Nations* (1978, pp. 569-72) believed that 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.

accepted. The process can be more readily understood if we distinguish four separate headings under which the Enlightenment made a difference to the growth of useful knowledge: agenda, capabilities, selection, and diffusion.[8]

Agenda. As already noted, the "Baconian Program" increasingly served as the key to the agenda of researchers. The idea was that knowledge was supposed to be "useful" — morally, socially, and increasingly, materially. Society was *improvable* through knowledge, and the purpose of the study of nature and experimentation was to help solve practical problems just as much and eventually more so than to satisfy human curiosity or to demonstrate the wisdom of the creator.[9] Many, if not most, of the natural philosophers of the age of Enlightenment agreed with Bacon's notions and acknowledged their intellectual debt to his ideas, including Diderot, Lavoisier, Davy, and the astronomer John Herschel (Sargent, 1999, pp. xxvvii-xxviii).

Consequently, many eighteenth-century scholars better known for their contributions to science used their analytical rigor and formal training to attack practical problems of production even if the direct connection of their discoveries to science is not always apparent. Among them were the greatest minds of the scientific Enlightenment. Leonhard Euler was concerned with ship design, lenses, the buckling of beams, and (with his less famous son Johann) contributed a great deal to theoretical hydraulics. The great Lavoisier worked on assorted applied problems as a young man, including the chemistry of gypsum and the problems of street lighting. Gottfried Wilhelm Leibniz, William Cullen, Joseph Black, Benjamin Franklin, Joseph Priestley, Humphry Davy, Tobern Bergman, count Rumford, and Johann Tobias Mayer were among the many first-rate minds who unabashedly devoted some of their efforts to solving mundane problems of technology: how to design calculating machines, how to make better and cheaper steel, increase agricultural productivity and improve livestock, how to build better pumps and mills, how to determine longitude at sea, how to heat and light homes and cities safer and better, how to prevent smallpox, and similar questions.[10]

The idea of turning research into useful knowledge was larger than the discovery of underlying general laws. Description and organization mattered as much, precisely as Bacon had argued. Many of the investigations of the eighteenth century were in the style of the "three C's": counting, cataloguing, classifying. Knowledge could only be useful if it was organized (Yeo, 2003). Taxonomy, often dismissed as a form of knowledge, was quite central to the market for ideas in the eighteenth century. The great figures were the Swedish botanist Carl Linnaeus and his French rival Georges-Louis Buffon, but many contemporaries followed them in attempts to gather more information about living beings so that farming and husbandry could be improved. In Britain the

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[8] The following pages are based on Mokyr, 2007b.

[9] The "business of science," John T. Desaguliers noted in the 1730s, was "to make Art and Nature subservient to the Necessities of Life in joining proper Causes to produce the most useful Effects" (1763, Vol. 1, p. iii). This was spoken by one of the leading Newtonians of the time, a man who made a career out of selling knowledge to others, a professional lecturer, a textbook writer, and a consultant to business.

[10] Of the many examples one could pick here, the career of René Réaumur (1683-1757) is most telling as the embodiment of the Enlightenment ideals. Although one of the most recognized scientists of his day (he was president of the French Académie Royale) his reputation today has been eclipsed by others. Yet in his day he worked on a variety of problems concerning the nature of iron and steel (he was first to suggest the chemical properties of steel), on problems of porcelain and glazing, he showed the feasibility of glass fibers and suggested that paper could be made from wood. He carried out a huge research program on entomology and pests, egg incubation, and worked on Meteorology and temperature measurement (hence the temperature scale still named after him).

paradigmatic figures were Erasmus Darwin and Joseph Banks, the authors of voluminous books on plants and animals, and Arthur Young and John Sinclair, who wrote extensively on agriculture. These highly descriptive writings did not have immediate results: agricultural productivity increased only slowly in the period of the classical Industrial Revolution, and insofar that it did, it was probably not much due to agricultural writings.[11] And yet, the demand side of the market for ideas was there, and the supply was on the way. The market was supported by the belief that more and better knowledge would eventually lead to human progress.

How effective were these efforts? The scholarly debate alluded to above, between those who feel that modern science played a pivotal role in the Industrial Revolution and those who do not, is more than the hackneyed question whether a glass is half full or half empty, because the glass started from almost empty and slowly filled in the century and a half after 1750. Scientists and science (not quite the same thing) had a few spectacular successes in developing new production techniques, above all the chlorine bleaching technique, the lightning rod, and the mining safety lamp. It did broaden the epistemic base of some techniques that had been in use for centuries, explaining — in part — why the things that were known to work actually did so.[12] The efforts made by Europe's most eminent learned men to improve practical techniques demonstrate that by the second half of the eighteenth century most scientists felt an acute responsibility to help improve the material world, and made a sincere effort to learn which problems bothered people toiling in the workshops and the fields. These efforts were reinforced by commercial interests, which created a literal market in knowledge. An increasing number of British natural philosophers and learned persons found it remunerative to rent out their services to manufacturers as consultants.[13]

Capabilities. The age of Enlightenment was the period in which the interaction between prescriptive knowledge and propositional knowledge started in earnest. Progress in science, it has long been noticed, is often constrained by limited instruments and research techniques. The scientific revolution advanced in part because new tools such as the telescope, the barometer, and the air pump allowed new observations and

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[11] Voltaire in his famed *Philosophical Dictionary* (1816, Vol. III, p. 91) caustically remarked that after 1750, many useful books written about agriculture were read by everyone but the farmers.

[12] At times, major breakthroughs remained barren for many years. Thus, the most spectacular insight in metallurgical knowledge, the celebrated 1786 paper by three of France's leading scientists, Monge, Berthollet, and Vandermonde that established the chemical properties of steel, had no immediate technological spin-offs. It was "incomprehensible except to those who already knew how to make steel" (Harris, 2001, p. 220). Harris adds that there may have been real penalties for French steelmaking in its heavy reliance on scientists or technologists with scientific pretensions. This dismissive remark seems exaggerated. Without the knowledge that carbon content determined the characteristics of steel, it would have been rather hard to make progress in this industry — though it took many years from that paper to Henry Bessemer and Robert Mushet. The knowledge, however, had clearly diffused to Britain by the 1820s, and was cited in widely available sources (e.g. *The Repertory of Arts, Manufactures and Agriculture* London: J. Wyatt, 1821, p. 369; Edward James Wilson, *The Artist's and Mechanic's Encyclopaedia*, Vol. 2,, Newcastle upon Tyne: Mackenzie and Dent, 1830, p. 67). In France, the Committee for Public Safety instructed the three scientists to write a 34-page pamphlet depicting how to make steel and distributed fifteen thousand copies. See Horn, 2006, pp. 147-48.

[13] Among the best-known ones in the early eighteenth century were the Scottish chemist William Cullen and the itinerant lecturer and Newtonian John T. Desaguliers. During the Industrial Revolution, the number of these consulting engineers expanded and they organized into the Smeatonian society named after John Smeaton, Britain's leading engineer. Among the consultants in high demand were John Whitehurst and Joseph Priestley, two members of the Lunar Society.

made new experiments possible. Price (1984) refers to scientific advances made possible by better tools as “artificial revelation.” In the eighteenth century this process accelerated. As a result, the rate of scientific discovery was stimulated by technological advances and in turn could help widen the epistemic base of techniques. It is this positive feedback effect that in the end led to the phased transition during which the entire dynamic of useful knowledge changed to produce sustained technological progress.

Examples are easy to find. The great advances made by Lavoisier and his pupils in debunking phlogiston chemistry were made possible by the equipment manufactured by his colleague Laplace, who was as skilled an instrument-maker as he was brilliant a mathematician. The invention of the first battery-like device that produced a steady flow of direct current at a constant voltage, namely Alessandro Volta’s pile of 1800, made it possible to separate elements in the newly proposed chemistry which in turn filled in the details of the landscape whose rough contours had been outlined by Lavoisier and his students.[14] Improved instruments and research tools played important roles in a range of “Enlightenment projects” that might be seen as technological improvements with poetic license. One such improvement was the use of geodesic instruments for surveying.[15] Time was measured with increasing accuracy, which was as necessary for precise laboratory experiments as it was for the solution to the stubborn problem of longitude at sea, one of the age of Enlightenment’s proudest successes. Experimental engineering also made methodological advances. John Smeaton was one of the first to realize that improvements in technological systems can be tested only by varying components one at a time holding all others constant (Cardwell, 1968, p. 120). In such systems, progress tends to be piecemeal and cumulative rather than revolutionary, yet Smeaton’s improvements to the water mill and steam engine increased efficiency substantially even if his inventions were not quite as spectacular as those of James Watt.

Another increased capability came from mathematics. The use of mathematics in scientific research was an ancient tradition, but advances in mathematics added new tools to the arsenal of engineers, and theoretical work in engineering advanced consequently and — with a considerable lag — expanded the supply of good ideas. Mathematics increasingly became a problem-solving technology and many great mathematicians lent their skill to computations that had useful applications in ballistics, engineering, astronomy, and navigation. Copernicus’s student, Rheticus, prepared complete tables for all six trigonometric functions, and Napier developed logarithmic tables. Computing tools such as Galileo’s “compass” and Pascal’s early calculating machine were designed, though the inability of mechanics to construct them at low prices limited their use. The input of formal mathematics into technical engineering problems in hydraulics and the design of better waterwheels was remarkable in the late eighteenth century. These attempts reflect both the potential and the difficulties of the learning process in applying the newly invented calculus to the dynamic problem of

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[14] As Humphry Davy, perhaps the most accomplished practitioner of the new electrochemistry, put it: Volta’s pile acted as an “alarm bell to experimenters in every part of Europe” (cited by Brock, 1992, p. 147).

[15] Jesse Ramsden designed a famous theodolite that was employed in the Ordnance Survey of Britain, which commenced in 1791. A comparable tool, the repeating circle, was designed by the great French instrument maker Jean-Charles Borda in 1775, and was used in the famed project in which the French tried to establish with precision the length of the meridian.

hydraulics.[16] Calculus, developed in the late seventeenth century, eventually found many applications in mechanical engineering as well as in construction.[17] Calculus, indeed, may be regarded a "General Purpose Principle," in the terminology of Lipsey, Bekar, and Carlaw, (2005): a multi-purpose tool that allowed for any function to be maximized and laws of dynamics written down and solved. Again, the French led their more pragmatic and less formal British colleagues. The three great French polytechniciens of the early nineteenth century, Gustave-Gaspard Coriolis, Jean-Victor Poncelet, and Louis Navier, placed mechanical and civil engineering on a formal base, and while the immediate impact of these advances on productivity is difficult to discern, it is hard to see how sustained progress in the longer run could have been made without it. The same holds for the study of electricity: eighteenth-century science grappled bravely with the topic, combining experimental work with theory. The mathematical work of Franz Aepinus (1759) provided the first theoretical epistemic base for the findings of experimentalists such as Musschenbroek, starting a long chain of investigation that would bear fruit more than a century later.

Selection. Ideas, small and large, are selected from larger menus of ideas that are proposed to people (Mokyr, 2006a). The selection process is determined by persuasion, and persuasion in free selection environments follows a set of criteria based on the rhetorical conventions of the time, these rhetorical conventions themselves a result of a selection process. Society constructs certain rhetorical conventions by which logic, evidence, and authority are admissible in arguments about ideas, and these conventions set the rules of the game, or the underlying institutions, in the competition between ideas to be accepted. A naive view of this process would only select among competing alternatives by the criterion of the maximal likelihood that they were "true." By that logic, astrology would have disappeared centuries ago. Once established, however, they tend to determine the prevailing ideology in society, including its religious beliefs as well as the scientific dominant doctrines.

What is left out here is coercion. Existing knowledge and ideas tend to develop into orthodoxy, and incumbents are defensive and jealous. Many entrenched elites found ingenious ways to perpetuate the status quo, so that intellectual innovation would only be admissible if it did not contradict the existing orthodoxy. Conservative establishments in science, religion, and political thinking argued that the predominant criterion for the acceptance of novel knowledge was that it be consistent with existing ideas. New ideas and techniques that were inconsistent with the intellectual or technological status quo, and could thus threaten the human capital of those who were in control of the existing knowledge, were to be suppressed, by force if necessary.[18]

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[16] The French mathematician Antoine Parent calculated that the maximum useful effect of a waterwheel was only 4/27th the natural force of the stream and that the optimal speed of the waterwheel was 1/3 that of the stream. These calculations were widely accepted, although they were incorrect and did not square with empirical observations. They were subsequently revised and corrected. Experimental work remained central and at times had to set the theorists straight (Reynolds, 1983).

[17] A celebrated example is the development of the theory of beams, in Charles Coulomb's celebrated 1773 paper "Statical Problems with Relevance to Architecture."

[18] The explanations of how such intellectual conservatism can be a rational response can vary (Kuran, 1988). It was often felt that a free marketplace for ideas might lead to subversion that threatened political stability (that is, the power base of the status quo), or that they might cause economic disruption such as unemployment. In other cases, still not entirely absent in our own age, disrespect toward the wisdom of elders or the presumption of appropriating powers that belong to a higher being ("playing God") are also resented. Symbolic tales like the sorcerer's apprentice and Prometheus embody the notion that innovation could be dangerous and should be contained and controlled.

Intellectual innovation could only occur in tolerant societies in which possibly outrageous ideas proposed by sometimes highly eccentric men would not incur violent responses against "heresy" and "apostasy." This was especially true in a world in which science, philosophy, and religion were inextricably connected. In the late middle ages, the intellectual innovations of the 12th and 13th centuries had rigidified into a Ptolemaic-Aristotelian canon that became increasingly intolerant of deviants. Cosmology and theology in the picture of the world that emerged were deeply intertwined and provided an intellectual foundation of the religious establishment. “The resulting system of the Universe was considered impregnable and final. To attack it was considered blasphemy” (Lipsey, Bekar and Carlaw, 2005, p. 237). Yet from 1500 on, this system came under increasing pressure and eventually collapsed.

How and why it did so is discussed elsewhere (Mokyr, 2005; 2007b), but it is important to see the Enlightenment as part of this changing set of criteria. Knowledge and beliefs were regarded as contestable at every level, and tolerance was raised to a level of a principle. Free entry into the market for ideas and the absence of repression were a high priority on which all Enlightenment thinkers were united. The ideals of tolerance and persuasion by argument and evidence, in which ideas were selected freely by individuals on merits other than acceptability by the ruling orthodoxy, eventually emerged successful. It held, somewhat naively, that selection among competing theories or observations was to be determined by criteria unrelated to politics, with acceptance exclusively determined by the rhetoric of knowledge itself: logic, rigor, experimental evidence, and observation. The triumph of this model became closely associated with the concept of the Enlightenment. All science and knowledge were riven with politics and their separation remained an ideal that in practice was never achieved, but degree is everything, and the politics of science changed considerably. What was determined in the age of Enlightenment was the principle of how scientific disputes were to be resolved when new information or insights emerged. In that regard, Lavoisier and Adam Smith were subject to the same rules. Consistency with earlier theories and respect for the knowledge of previous generations was to have little impact on selection, at least in theory.[19]

The main insight regarding the nature of new useful knowledge that Francis Bacon — himself no scientist — left to his Enlightenment admirers was the legitimacy of experimental research in progress. In that regard, perhaps, his philosophy in part formalized what was already carried out by many natural philosophers and alchemists in practice, but his thinking clearly helped place experimental science at center stage of scientific progress. Whenever the orthodoxy was contradicted by experiment, the orthodoxy was challenged, and Gillespie (1960, p. 79) has stated that experimental science has become practically a synonym for ‘modern science’. The importance of experimental work to the Industrial Revolution was enormous: the careers of James Watt, John Smeaton, James Keir, John Roebuck, Humphry Davy, Joseph Priestley, Count Rumford, Michael Faraday and countless other inventors cannot be imagined without experimental work guiding them. Especially when the epistemic base of a technique is quite narrow so that the outcome of a procedure cannot be predicted, there

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[19] John Taylor, a teacher at one of Britain’s dissenting academies, Warrington Academy, told his pupils in 1757 that “if at any time hereafter any principle or sentiment by me taught or advanced, or by you admitted and embraced, shall upon impartial and faithful examination appear to you to be dubious or false, you either suspect or totally reject that principle or sentiment” (cited by Reid, 2006, pp. 8-9).

is no real substitute for experimental work to guide the selection process of useful knowledge.

The other element in selection is the concept of "open science" to which I will return below. The Scientific Revolution saw the emergence of a set of norms and customs in which discoveries and advances in natural philosophy were placed in the public domain as soon as possible, with the author demanding credit for priority. One consequence of this procedure is the concept of peer review, whether before or after publication. For non-experts, selection was made more efficient because one could make a reasonable presumption that new knowledge had been vetted by other specialists. That such presumptions are often mistaken does not reduce the effect; without it, there is always no way such selection can be made. Some periodicals, especially the proceedings of the Royal Society and other official academies and, much later, high-prestige periodicals such as Nicholson's *Journal* and François Rozier's *Observations sur la Physique, sur l'Histoire Naturelle, et sur les Arts* fulfilled a similar function.

Diffusion. As Dasgupta and David (1994) have noted, knowledge requires an institutional set-up unlike any other market because the market for ideas in many ways resembles an open-source technology. Open science, as many scholars have stressed, was the key to the rapid changes in the market for ideas because its very purpose was to disseminate new ideas and offer them to the marketplace. The incentives in such a market work quite differently from those in other markets, and are most comparable to modern open-source technology networks (Lerner and Tirole, 2004). In such networks, all new knowledge is placed in the public realm and judged by peers. Success is mostly a result of a signaling contest, in which reputations are maximized. Such reputations are then correlated with a variety of benefits, but also appear in the preferences of the actors directly. In seventeenth- and eighteenth-century Europe, such reputations were critical both for appointments at universities and patronage (David, 2004), and contributed materially to the emergence of open science.

The Enlightenment picked up on this trend. It was, in large part, about communication. From the point of view of economic history, what is most interesting here is the reduction of access costs. Knowledge is a non-rivalrous good, and in theory, the source can share it costlessly. No such argument can be made for the recipient, who incurs a variety of search, transfer, and verification costs. These costs depended on both technological and cultural factors. Inventions such as paper, printing, and the telegraph, as well as improvements in transportation and postal services were an important factor. There can be no question, however, that institutions played a major role here, and that the emergence of open science and a culture of sharing knowledge as well as a growing aversion to the secrecy associated with useful knowledge in earlier times, so typical of the age of Enlightenment, were critical in reducing access costs (Eamon, 1994). If knowledge were to grow, it needed specialization, a "division of knowledge."[20] Yet such a specialization depended crucially on low access costs.

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[20] Smith ([1978] 1757, p. 570) argued outright that "speculation in the progress of society...like every trade is subdivided into many different branches ... and the quantity of science is considerably increased by it." The idea caught on. Joseph Priestley wrote in 1768 that "If, by this means, one art or science should grow too large for an easy comprehension in a moderate space of time, a commodious subdivision will be made. Thus all knowledge will be subdivided and extended, and knowledge, as Lord Bacon observes, being power, the human powers will be increased ... men will make their situation in this world abundantly more easy and comfortable" (Priestley, 1768, p. 7).

Access costs were also important because they governed, so to speak, both the vertical and horizontal movements of useful knowledge. By vertical movements I mean the signals sent between those who controlled propositional knowledge, the *savants*, and those who were concerned with prescriptive knowledge, *fabricants*. As I emphasized elsewhere (Mokyr, 2002), the connection between those two social spheres is critical to the question of which segments of propositional knowledge will end up being "mapped" into the set of available techniques, in other words, what kind of inventions is one to expect? This, indeed, is among the hardest problems in economic history. Horizontal movement of useful knowledge provides would-be inventors and implementers with best-practice scientific knowledge underlying the technique in question (which may not be very good), and it sends would-be scientists and experimentalists signals about the needs of those in the workshops and the fields.

Indeed, it is astonishing that in many cases societies seem to have had technological opportunities that they could have exploited given the knowledge they had, but for one reason or another the mapping does not seem to have taken place. Why, for instance, did the Romans never invent eyeglasses despite their knowledge of glass or optics, or succeed in casting iron or use navigational instruments at sea? Part of the answer must be the point I made above: the communications (or *passerelles* as Hilaire-Perez, 2000, has called them) between those who make things and have a "feel" for what is needed, and those with the mathematical or scientific knowledge to realize how the problem is to be solved needs to be tight and effective for this horizontal signalling.[21]

But there were other reasons why declining access costs played such a central role in the economic transformation of Europe. Much invention takes the form of analogues to and combinations of existing techniques, or combined knowledge from diverse fields in what we might call technical hybrids or recombinations.[22] It was thus critical that knowledge of techniques in use in other industries and regions be made accessible. Furthermore, such knowledge would help prevent inventors from entering blind alleys, both in terms of re-inventing the wheel and from trying things that would not work (though the latter, of course, could be quite ambiguous).

Access to knowledge can be usefully analyzed by distinguishing between codified and tacit knowledge. The former depended crucially on the written word, especially on print. The eighteenth century experienced a veritable explosion of books that made useful knowledge accessible. The discovery that information could be made more accessible by alphabetization was exploited in full in the eighteenth century. The document most widely associated with the Enlightenment, Diderot and d'Alembert's *Encyclopédie,* contained numerous articles on technical matters, lavishly illustrated by

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[21] Stewart (2007, p. 13) notes that Enlightenment thinkers considered the distinctions between scholars and craftsmen downright harmful "to the philosophical enterprise" though they were regarded equally harmful to material progress in general. Some were optimistic: Humphry Davy wrote in 1802 that "in consequence of the multiplication of the means of instruction, the man of science and the manufacturer are daily becoming more assimilated to each other" (Davy, 1840, vol. 2, p. 321). Count Rumford, however, noted impatiently in 1799 that "there are no two classes of men in society that are more distinct, or that are more separated from each other by a more marked line, than philosophers and those who are engaged in arts and manufactures" and that this prevented "all connection and intercourse between them." Thompson, 1876, pp. 743-745.

[22] This phenomenon was already realized on the eve of the Industrial Revolution: Joseph Moxon wrote in the 1670s that "The Trades themselves might, by a Philosopher, be Improv'd ... I find that one Trade may borrow from many Eminent Helps in Work of another Trade" (Moxon, 1703, preface).

highly skilled artists who, in most cases, were experts in their fields.[23] Encyclopedias and indexes to "compendia" and "dictionaries" were the search engines of the eighteenth century. In order to be of practical use, knowledge had to be organized so that it could be selected from. Alphabetization was one way to do this, the organization of science into categories another (Yeo, 2003). Some encyclopedias and dictionaries were designed to be efficient search engines and to reduce access costs.[24] The number of scientific periodicals in the eighteenth century soared. In the early decades the number of learned periodicals (all areas) in all of Europe was still fairly modest: an average of 21 per year in the first decade of the eighteenth century, 34 in 1721/30, and 77 in 1741/50. In the 1790s, this number had soared to 531 (computed from Kronick, 1991, see Mokyr, 2005).

Tacit knowledge, passed in person, went through a similar flourishing. Stewart, 1992, has described in great detail how science became "public," sold to the public in coffee houses, country inns, and a variety of societies and academies in which public lectures and meetings were held. In 1700 there were 2000 coffee houses in London alone, many of which were the locations of lectures. Over the course of the century, both formal and informal meeting places increased exponentially, the most famous being the Birmingham Lunar Society and the London Chapter coffee house. The Royal Institution, founded by Count Rumford and Joseph Banks in 1799, provided public lectures on scientific and technological topics. Its stated purpose in its charter summarizes what the Industrial Enlightenment was about: it was established for "diffusing the knowledge, and facilitating the general introduction, of useful mechanical inventions and improvements; and for teaching, by courses of philosophical lectures and experiments, the application of science to the common purposes of life."[25]

Intellectual Property Rights and the Enlightenment

Enlightenment thought was reasonably unanimous about its belief that progress through expanded and accessible useful knowledge was possible and desirable, Jean-Jacques Rousseau being perhaps the most noticeable exception. When it came to Intellectual Property Rights, however, the new ideology found itself painfully torn between a number of conflicting views. One was the visceral opposition to monopolies and restrictions of any kind on free entry. This instinct was reinforced by the Baconian notion that useful knowledge should be shared and that its accumulation was a fundamentally cooperative endeavor. In such an ideal world, a patent system which limits usage is not desirable. At the same time, *philosophes* had to confront the notion that if a society wished to promote technological change, it needed to create the economic incentives for inventive activities to take place. Moreover, the belief in the

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[23] Pannabecker (1996, 1998) points out that the plates in the Encyclopédie were designed by the highly skilled Louis-Jacques Goussier who eventually became a machine designer at the Conservatoire des arts et métiers in Paris. They were meant to popularize the rational systematization of the mechanical arts to facilitate technological progress.

[24] Croker et al., 1764-66 serves as an interesting example. The title page of their book reads "in which the whole circle of human learning is explained and the difficulties attending the acquisition of every art, whether liberal or mechanical, are removed in the most easy and familiar manner." The topics covered ranged from heraldry and rhetoric to hydraulics and pneumatics. Many of the articles were quite advanced and required considerable prior knowledge if the reader were to benefit from them.

[25] The lectures given by Humphry Davy were so popular that the carriages that brought his audience to hear him so clogged up Albermarle Street in London that it was turned into the first one-way street of the City.

sanctity of private property was profound, and considered a natural law, a fundamental human right, an idea that found its way into a declaration made by the French National Assembly in 1790 and the United States Constitution a few years earlier. The latter, perhaps, more than anything else, has helped establish IPRs as a paradigmatic Enlightenment institution, but such an inference would be rash.

Opponents of the patent system identified it as a rent-seeking device, often used to block new entry, conveniently ignoring the fact that those who resisted patents were sometimes motivated by protecting their own incumbency from unwelcome entrants. Among those opponents, guilds were uppermost (MacLeod, 1988, pp. 83, 113). It was also noted in the late seventeenth century that patentees often were not the best qualified persons to exploit the inventions.[26] A different critique, but equally telling, was made by J.T. Desaguliers, who pointed out (1763, Vol. 2, p. viii) that a patent was often interpreted by investors as an official imprimatur of the quality of an invention (much like modern venture capitalists), and that there were “several persons who have money, ready to supply boasting Engineers with it in the hope of great Returns, and especially if the project has the Sanction of an Act of Parliament to support it, and then the Bubble becomes compleat and ends in Ruin.” The problem remained how society should reward those who gave their time and money to develop knowledge that was of great benefit to the rest of society. Such rewards, it was understood, needed to be established if society was to enjoy the fruits of sustained technological progress.

Of those incentives, the patent system was one option but by no means the only one. Many economists still think of it as the cornerstone of such an incentive system (Khan, 2004) but the notion has come under criticism. The debate is far from new. Goethe may have been somewhat naive when he wrote that the British patent system's great merit was that it turned invention into a "real possession, and thereby avoids all annoying disputes concerning the honor due" (cited in Klemm, 1964, p. 173). In his *Lectures on Jurisprudence* (1762-66 [1978), pp. 83, 472], Adam Smith admitted that the patent system was the one monopoly (or “priviledge” as he called it) he could live with, because it left the decision on the merit of an invention to the market rather than to officials. Smith thought, somewhat unrealistically, that if an “invention was good and such as is profitable to mankind, [the inventor] will probably make a fortune by it.”

Not all inventors sought such rewards, and certainly not many actually attained them. Many inventors in the Industrial Revolution placed their inventions at the public’s disposal, and others for one reason or another, failed to secure a patent or subsequently lost it.[27] Yet the politicians had come to realize that rewarding inventors who made significant contributions to the nation’s technological capabilities was good public policy. Both Samuel Crompton, the inventor of the mule, and Edmund Cartwright, the inventor of the power-loom, were rewarded by Parliament with considerable sums, though they captured but a minute fraction of the social surplus that their inventions

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[26] Andrew Yarranton, a tin-plater, found his business harmed by a patentee incapable of working it properly (MacLeod, 1988, p. 184).

[27] Scientists who made inventions of considerable importance, such as Count Rumford, Benjamin Franklin, Joseph Priestley, or Humphry Davy, usually wanted credit, not profit. Some entrepreneurs, too, refused to take out patents out of principle. The great engineers, too, largely stayed away from the patent system. Abraham Darby II declined to take out a patent on his coke-smelting process allegedly saying that “he would not deprive the public from such an acquisition” (cited by McLeod, 1988,p. 185), although his father, the founder of the dynasty, did take out a patent on his sand-casting process (1708).

eventually created. A petition for the estate of Henry Cort was denied by Parliament, but the fact that other ironmasters entered a subscription for the benefit of Cort's widow demonstrates that contemporaries sensed significant spillovers here. The pioneers of paper-making machines, Henry and Sealy Fourdrinier, too, were awarded a grant of £20,000 by a Parliamentary committee (after many manufacturers testified that the continuous paper machines had been of huge benefit to their respective branches), though this amount was later reduced to £7,000 and paid as late as 1840, when Henry was already in his seventies. The scientist William Sturgeon, one of the pioneers of electrical technology in the 1830s, fell on hard times toward the end of his life, and was awarded a one-off payment of £200 plus a small pension by Lord John Russell's government. In all these cases, and many others, there was an explicit recognition that these people had added to the well-being of the realm; in other words, they had produced positive externalities. But they also reflect a recognition that invention was costly and risky, and that if society wanted to generate a continuous stream of technical improvements, it had to make the activity that generated innovation financially attractive.

Britain was not the only Western nation to take this view. France and the Netherlands had patent systems in which innovations could yield considerable benefits to their propagators. In Britain, however, the state only recognized and enforced the inventor's right (Hilaire-Perez, 2000). It did not normally take it upon itself to evaluate the invention's contribution to society. The type of encouragement given to inventors in Britain differed thus from the French system during the *ancien régime*, where government agents were put in charge of evaluating the contribution of certain inventions to the realm. The difference between the two systems can be overstated: at times the British authorities recognized the national interest and were willing to act to pursue it aggressively. An example was the Board of Longitude, established in 1714 by Parliament, which promised a large sum to the person who successfully cracked the age-old problem of measuring longitude at sea.

It seems that the main effect of the patent system on innovation was to goad potential inventors into believing that they, too, could make as much money as the Lombe brothers or James Watt. In point of fact, precious few ever did, but the expectation may have been enough for many. Britain's patent system was not exactly inviting: it charged a patentee £100 for the right to patent, not counting the costs of traveling to and staying in London (Khan and Sokoloff, 1998). Moreover, many patents were infringed upon and judges were often hostile to patentees, considering them monopolists.

The exact impact of the patent system and other positive incentives on the technological creativity that eventually helped produce a more prosperous nation is hard to establish. Recently some economists have gone so far as to dismiss it altogether. Boldrin and Levine have argued that intellectual property rights have been unimportant in bringing about economic growth, and have specifically pointed to the Industrial Revolution as a period that provides "a mine of examples of patents hindering economic progress while seldom enriching their owners and of great riches and economic successes achieved without patents" (Boldrin and Levine, 2005, chapter 4, p. 7). Such an extreme position neglects the important qualification that what the patent system was important *ex ante* in giving would-be inventors was hope for success, in a fashion not dissimilar to why people purchase lottery tickets. If no one ever won the lottery, people would stop buying tickets; but the number of winners need not be very large to keep hope alive. Yet it exemplifies the complexity of the institution.

The patent system also was a means for the diffusion of useful knowledge: once a patentee filed, he or she had to divulge the existence of the invention and in principle forewent the protection of secrecy. After *Liardet vs. Johnson* (1778), the patentee was required to explain the invention in such a manner than anyone familiar with the technique could understand and reproduce it. While access to the filed patent remained cumbersome, it was easier than industrial espionage or reverse engineering.

The problems with IPRs underline the difficulty in separating exactly those elements we think of as "institutional" and those that properly belong to the category of "technological creativity." Such categories are creations of our minds, which help us sort out complex historical relations, but they do not have a historical "reality" of their own. Yet if we are to understand the Industrial Revolution and the germination and birth of the British economy, some kind of analytical framework that classifies different phenomena is necessary.

The Emergence of Modern Economic Growth

For many decades, the Enlightenment had little palpable impact on production. What is astonishing, in retrospect, is that the belief in the value of useful knowledge survived so long in the face of a lack of results. The world turned out to be more messy and complex than the early and hopeful proponents of the Baconian Program realized, as H.F. Cohen (2004, p. 123) has suggested. The natural philosophers on whom so many placed their hopes did not know enough and lacked the tools to solve most of the pressing problems quickly, and many of the early inventions, especially in textiles, were driven by mechanical dexterity, intuition, experience-driven insights, and similar abilities. Indeed, while the results of the Industrial Enlightenment in the eighteenth century were few and far between, those of the agricultural and medical Enlightenments were even less impressive. Farming practices, with some exceptions, were largely unaffected by the huge literature that Enlightenment writers interested in agriculture, known as *agronomes*, produced.[28] Things were no better in medicine, where high hopes that increased knowledge would cure the worst ills afflicting mankind were sorely disappointed. Again, there were some successes, but they remained local and limited triumphs until the epistemic base of medical techniques was expanded so that infectious disease was better understood.[29]

It is remarkable that belief in the mission remained indefatigable in the face of continuous frustration and disappointment (although the Royal Society itself lost its fascination with technology after 1700). And there was plenty of frustration and disappointment. A case in point is William Cullen, a Scottish physician and chemist. His work "exemplifies all the virtues that eighteenth-century chemists believed would flow from the marriage of philosophy and practice" (Donovan, 1975, p. 84). Ironically,

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[28] An exception was the success that animal breeders such as Robert Bakewell had in producing improved varieties of sheep and cattle, such as the New Leicester sheep and the Yorkshire shorthorn and the introduction of improved plough designs.

[29] Among those were the discovery by British naval officers that fresh fruits and vegetables could prevent scurvy, the use of cinchona bark (quinine) to fight off the symptoms of malaria, the prescription of foxglove (now known as digitalis) as a treatment for edemas and atrial fibrillation (first recommended by Dr. William Withering, a member of the Lunar Society, in 1785), the consumption of cod liver to prevent rickets, and above all the miraculous vaccination against smallpox discovered by Jenner in 1796.

however, this marriage remained barren for many decades. Cullen's prediction that chemical theory would yield the principles that would direct innovations in the practical arts remained, in the words of the leading expert on eighteenth-century chemistry, "more in the nature of a promissory note than a cashed-in achievement" (Golinski, 1992, p. 29). Manufacturers needed to know why colors faded, why certain fabrics took dyes more readily than others, and so on, but as late as 1790, best-practice chemistry was incapable of helping them much (Keyser, 1990, p. 222). Before the Lavoisier revolution in chemistry, it just could not be done, no matter how suitable the social climate: the minimum epistemic base simply did not exist.

In many other areas, despite the best of efforts and intentions, the new research agenda yielded few tangible results. Another example is the exploration of electricity. The eighteenth-century natural philosophers were fascinated by this strange force, and believed that once tamed, it held great promise. While advances in electricity such as the Leyden jar (invented in 1746), the discovery of different levels of conductivity, and the finding that electricity could be transmitted over considerable distances all stirred many an imagination, and some entertaining uses were found for the mysterious phenomenon, practical applications had to await the breakthroughs of Oersted, Faraday, and Ampère in the first half of the nineteenth century. An exception was Franklin's lightning rod (1749), one of the first useful pragmatic applications of experimental science.

It is important to realize how much effort was spent in this age on unsuccessful, or what may seem to us completely useless, research in chemistry, medicine, botany, electricity, and many other areas. Rather than indicating an inefficient allocation of resources, this shows of course that new knowledge creation is inherently wasteful. Yet the belief that somehow the systematic study of nature could yield insights that would eventually enrich and improve industry and agriculture never faded, no matter how remote the chances were. Such was the profound influence of the Enlightenment.

Although the Enlightenment is commonly considered to have ended in 1789, its effects on the economy were, as already indicated, most pronounced in the nineteenth century. The triumph of Enlightenment thought came in the growing influence of liberal political economy, which gradually dismantled the regulatory state in the first half of the eighteenth century, and between 1780 and 1830 repealed many of the limitations on the free market and reduced rent-seeking. But more than anything else, the momentum of technological progress was preserved rather than dissipated. While economic historians have not found much productivity growth during the classical Industrial Revolution (Antras and Voth, 2003), after 1830 productivity starts to increase and by 1850 its effects on real wages and the standard of living become apparent.

The second stage of the Industrial Revolution adapted ideas and techniques to be applied in new and more industries, improved and refined earlier inventions, extended and deepened their deployment, and eventually these efforts showed up in the productivity statistics. Among the remarkable later advances we may list the perfection of mechanical weaving after 1820; the invention of Roberts's self-acting mule in spinning (1825); the extension and adaptation of the techniques first used in cotton and worsted to carded wool and linen; the improvement in the iron industry through Neilson's hot blast (1829) and related inventions; the continuous improvement in crucible steelmaking through coordinated crucibles (as practiced for example by Krupp in Essen); the pre-Bessemer improvements in steel thanks to the work of Scottish steelmakers such as David Mushet (father of Robert Mushet, celebrated in one of

Samuel Smiles's *Industrial Biographies*), and the addition of manganese to crucible steel known as Heath's process (1839); the continuing improvement in steam power, raising the efficiency and capabilities of the low pressure stationary engines while perfecting the high pressure engines of Trevithick, Woolf, and Stephenson, and adapting them to transportation; the introduction of ever-more efficient water mills, including the invention of the turbine by Benoît Fourneyron in 1837; the advances in chemicals before the advent of organic chemistry (such as the breakthroughs in candle-making and soap manufacturing thanks to the work of Eugène-Michel Chevreul on fatty acids); the introduction and perfection of gas-lighting and its subsequent dissemination; the breakthroughs in high-precision engineering and the development of better machine-tools by Maudslay, Whitworth, Nasmyth, Rennie, the Brunels, the Stephensons, and the other great engineers of the "second generation"; the growing interest in electrical phenomena leading to electroplating; and the work by Hans Oersted and Joseph Henry establishing the connection between electricity and magnetism, leading to the telegraph in the late 1830s. In other industries such as cement, glass, paper, and food processing, there were major improvements. Many of those depended in ever-growing degrees on wider epistemic bases: the knowledge base was growing and those who needed it, whether they were inventors or engineers, had access to that knowledge.

While the years between 1830 and 1870 were the age of the railroad and the telegraph and witnessed the triumphs of British technology at the Crystal Palace exhibition in 1851, the full triumph of technology was only secured after 1870 with the arrival of cheap steel, electrical power, chemicals, and other advances associated with the second Industrial Revolution. Yet historians, celebrating the second Industrial Revolution as the central event of economic history and the true beginning of modern technological society (e.g. Smil, 2006), need to confront the importance of the precedence of the first Industrial Revolution and the Enlightenment that made it possible.

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