The Intellectual Origins of Modern Economic Growth

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The intellectual origins of the Industrial Revolution are traced back to the Baconian program of the seventeenth century, which aimed at expanding the set of useful knowledge and applying natural philosophy to solve technological problems and bring about economic growth. The eighteenth-century Enlightenment in the West carried out this program through a series of institutional developments that both increased the amount of knowledge and its accessibility to those who could make best use of it. Without the Enlightenment, therefore, an Industrial Revolution could not have transformed itself into the sustained economic growth starting in the early nineteenth century.

Economic growth was not a novelty in 1800. In a celebrated passage, Adam Smith had noted that the "annual produce of land and labour" had been growing in Britain for a long time.[1] Yet there is something distinctive in the changes that occurred in the economies of the West after the Industrial Revolution that seem to confirm our intuition that something genuinely important had happened. To be sure, technological innovations, institutional reforms, and fresh ideas do not affect the aggregate level of economic activity abruptly: they need to diffuse from region to region, from activity to activity, cross boundaries and seas, be evaluated, adapted, and refined. Their promoters have to dislodge the entrenched, persuade the skeptic, and reassure the fearful. It is not surprising, therefore, that whatever we identify precisely as the Industrial Revolution after 1760 took its sweet time to start affecting GDP per capita in the West in earnest.[2]

The Journal of Economic History, Vol. 65, No. 2 (June 2005). ISSN 0022-0507.

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This Presidential Address was delivered at the sixty-fourth annual meetings of the Economic History Association in San Jose, California, 11 September 2004. The comments and suggestions of Kenneth Alder, Maristella Botticini, Margaret Jacob, Edward Muir, Cormac Ó Gráda, Avner Greif and Richard Unger are acknowledged. I am indebted to Fabio Braggion, Chip Dickerson, Hillary King, and Michael Silver for research assistance.

[1] Smith, *Wealth of Nations*, pp. 365–66. Modern economic historians have reached similar conclusions. While none of their methods are uncontroversial, their unanimity seems to indicate that the "assumption" of modern economists such as Robert Lucas and Oded Galor that there was no economic growth before 1800 is a gross oversimplification. See for instance Clark, "Secret History"; and Snooks, "New Perspectives."

[2] There is a substantial literature that asks with Jeffrey Williamson "why was economic growth so slow during the Industrial Revolution?" although the answers tend to be different from the ones given by him. See Williamson, "Why Was British Growth," pp. 687–712. For some suggested answers see Mokyr, "Editor's Introduction," pp. 12–17.

Modern economic growth differs from the processes that Smith identified and that made Britain and the rest of Western Europe so much richer in 1700 than they had been in 1066. To the hard-nosed scholar who insists that "it was all only a matter of degree," one response is that "in economic history, degree is everything." There is a *qualitative* difference between an economy in which GDP per capita grows at 1.5 percent and one in it which grows at 0.2 percent. Another response is that it was *not* just a matter of degree. It was *qualitatively* different in at least three fundamental aspects. First, growth gradually ceased to be a niche phenomenon. Before 1750, growth had been limited to relatively small areas or limited sectors, often a successful city state, a capital of a powerful monarchy, or a limited agricultural region. These niches had to spend much of their riches to protect their possessions against greedy neighbors, real-life manifestations of Mancur Olson's "roving bandits" who often killed entire flocks of golden-egg-laying geese. After the Industrial Revolution, it became a more aggregative phenomenon, with a substantial number of economies becoming members of the much-coveted "convergence club." Second, pre-1750 growth, such as it was, was dominated by institutional change in its widest sense: law and order, the establishment of commercial relations, credit, trust, and enforceable contracts created the preconditions for wealth to expand through more efficient allocation, exchange and investment.[3] Technological change, while never quite absent, was usually too slow and too localized to assume the dominant role it was to take later. Third, premodern growth was normally not sustainable and remained vulnerable to set-backs and shocks, both man-made and natural. The economic glories of the Dutch Republic and Venice had melted away by 1800, just as those of early sixteenth century Spain had vanished by the death of Philip II.[4] In the late eighteenth century the relative contribution of technological progress to economic growth compared to other elements began to increase, and the institutional basis supporting this progress was transformed. The result was the Industrial Revolution. It may have been slow, it may have been not all that industrial and even less revolutionary, it may not even have been wholly British, but it was the taproot of modern economic growth.

How do we explain this change? What has been missing, so far, is a full appreciation of the importance of *useful knowledge.* Economic decisions are made by individuals on the basis of certain beliefs they hold and knowledge they possess. It recent years, it has once again become "kosher" if not quite de rigueur to speak of "cultural beliefs" following Avner Greif's pathbreaking work on the emergence of institutions that made trade

[3] See Greif, *Institutions.*
[4] De Vries and Van Der Woude. *First Modern Economy*; and Drelichman, "American Silver."

possible in stateless and even largely lawless societies.[5] Douglass North refers to shared cultural beliefs and as the "scaffolds" on which institutions are built.[6] But Greif and North are primarily interested in the kind of beliefs that people hold about one another, how others will behave under certain circumstances. My interest here is about the beliefs people held about their physical milieu. In my *Gifts of Athena* I refer to these beliefs as "useful knowledge," but of course they are but beliefs about the physical environment and natural phenomena, held with higher or lower degrees of unanimity and confidence ("tightness"). Yet all societies have consensus-shaping mechanisms, which determine what kind of beliefs will predominate. I suggest in what is to follow that the change in the rate and nature of economic growth in the West must be explained through developments in the intellectual realm concerning this "useful knowledge."

The short answer as to why the West is so much richer today than it was two centuries ago is that collectively, these societies "know" more.[7] This does not necessarily mean that each *individual* on average knows more than his or her great-great grandparent (although that is almost certainly the case given the increased investment in human capital), but that the social knowledge, defined as the union of all pieces of individual knowledge, has expanded. Greater specialization, professionalization, and expertization have meant that the total amount of knowledge that society controls is vastly larger than ever before. The effective deployment of that knowledge, scientific or otherwise, in the service of production is the primary—if not the only—cause for the rapid growth of Western economies in the past centuries. The huge literature that has accumulated on the topic in recent years has been ably summarized by Helpman's recent book.[8] In what follows, I propose a slightly different approach, based largely on the experience of the Western economies in the eighteenth century.

THE INTELLECTUAL ROOTS OF THE INDUSTRIAL REVOLUTION

Economic historians like to explain economic phenomena with other economic phenomena. The Industrial Revolution, it was felt for many decades, should be explained by economic factors. Relative prices, property rights, endowments, demand factors, fiscal and monetary institutions, investment, savings, exports, and changes in labor supply have all been put forward as possible explanations.[9] Between the presence of coal, the Glo-

[5] Greif, "Cultural beliefs"; and Temin, "Is it Kosher," pp. 267–87.
[6] See North, *Understanding the Process*.
[7] For a more detailed statement on this, see Mokyr, *Gifts*.
[8] Helpman, *Mystery*.
[9] For a full survey, see Mokyr, "Editor's Introduction," pp. 1–127.

rious Revolution, a mobile and open society, the control of a colonial empire and a powerful navy, a greedy middle class, a productive agriculture, an unusually high supply of skilled artisans and mechanics serving the private sector, and assorted other stories, a veritable smorgasbord of explanations for Britain's success has been offered. The reader is invited to pick and choose, or just pile them one on top of the other and find the explanations satisfactory by sheer quantity. Yet these approaches have all suffered from the "endogenous growth problem": none of them can carry the weight of the explanandum without relying on technological change. If technology was at the heart of the Industrial Revolution, why was it changing at a rate more rapid and on a scale more widespread than ever before, and why did it accelerate in the nineteenth century instead of fizzle out?

One possible reason why this literature has been inconclusive is that many scholars have sought the causes for the economic change in the West as something particular to *Britain*. Yet this approach might be misleading. The Industrial Revolution was a *Western* phenomenon. It was more than just a British affair, if less than a "European" affair. The causes for the differences in technological patterns and rates of development between the several European economies that by 1914 constituted the core of the convergence club is a source of a fascinating and instructive debate, but may not hold the keys to the riddle of the Industrial Revolution. Britain's position as the lead car in the Occident Express that gathered speed in the nineteenth century and drove away from the rest of the world is of tremendous interest, but it does not tell us much about the source of power. Was Britain the engine that pulled the other European cars behind it, or was the Western world like an electric train deriving its motive power from a shared source of energy? If so, what was this source?

One answer, I submit, that thus far has not received nearly enough attention from economic historians involves the intellectual changes that occurred in Europe before the Industrial Revolution. These changes affected the sphere of useful knowledge, and its interaction with the world of production. In a sense, this statement is so obvious as to be almost trivial, but the insight has been clouded by the somewhat tedious debate on the role of science in the Industrial Revolution. As economic historians have known for many years, it is very difficult to argue that the scientific revolution of the seventeenth century we associate with Galileo, Descartes, Newton, and the like had a direct impact on the pivotal technological breakthroughs of the Industrial Revolution. To be sure, a few important inventions, especially before 1800, can be directly attributed to great scientific discoveries or were dependent in some way on scientific expertise.[10] Yet the bulk of the advances in physics, chemistry, biology, medicine, and other areas occurred too late to have an effect on the industrial changes of the last third of the eighteenth century. The scientific advances of the seventeenth century, crucial as they were to the understanding of the universe, were largely peripheral to the main thrust of eighteenth-century technology that we think of as the Industrial Revolution. During the age of Enlightenment, and especially the decades after 1750, much of Europe witnessed a flourishing of interest in the application of useful knowledge to the arts and crafts, as well as to agriculture. Yet, as Charles Gillispie has remarked, in the eighteenth century, whatever the interplay between science and production may have been, "it did not consist in the application of up-to-date theory to techniques for growing and making things."[11]

True enough: in the early stages of the Industrial Revolution, many of the important advances owed little to science in a direct way. However, had technological progress been independent of what happened at the loftier intellectual level, had it consisted purely of disseminating best-practice existing procedures, standardizing them, and hoping for learning-by-doing effects, the process would eventually have run into diminishing returns and fizzled out. What was it that prevented that from happening in the decades following the burst of macroinventions we identify with the classic Industrial Revolution? In part, it is our own thinking of "science" that is at fault, because we tend to think of science as more "analytical" than descriptive. The eighteenth century, however, spent an enormous amount of intellectual energy on describing what it could not understand. The three "C's"—counting, classifying, cataloguing—were central to the Baconian program that guided much of the growth of useful knowledge in the century before the Industrial Revolution. Heat, energy, chemical affinities, electrical tension, capacitance, resistivity and many other properties of materials from iron to bricks to molasses were measured and tabulated before they were, in some sense, "understood." Measurement itself was not novel in the eighteenth century; the accuracy, thoroughness, and reliability, the scope of phenomena and quantities being measured, and the diffusion of this knowledge surely were.

[10] The *opus classicus* on this topic remains Musson and Robinson, *Science and Technology.* For the best recent statement, see Jacob, *Scientific Culture* and "Cultural Foundations," pp. 67–85.

[11] Gillispie, *Science . . . End of Old Regime,* p. 336. For canonical statements on the "unimportance of science" see Hall, "What Did the Industrial Revolution?"; Neil McKendrick, "Role of Science"; Mathias, "Who Unbound Prometheus?" John R. Harris has been even more skeptical of the importance of science relative to "tacit" skills and has even argued that France's backwardness in steelmaking was in part due to its reliance on scientists, who at first gave misleading and later rather useless advice to steel makers; compare Harris, *Industrial Espionage*, pp. 219–21.

In the nineteenth century the connection between science and technology became gradually tighter, yet remained sufficiently uneven and heterogeneous to make any dating very hazardous. Scholars such as Nathan Rosenberg and Derek Price have argued for the causality running mainly from technology to science rather than the reverse.[12] Arguably, however, science and technology were both endogenous to a third set of factors that determined the direction and intensity of the intellectual pursuits that led to advances in both. In what follows, I shall try to identify what this set consists of, document it in some detail, and then consider to which extent these factors may be regarded as "exogenous." I propose that one source of the success of the Industrial Revolution must be found in the developments in the area of the generation and diffusion of useful knowledge that occurred in Europe before and around 1750, and specifically in the Enlightenment.

The confusion surrounding the role of science in the eighteenth century on economic developments and the rather tiresome debate regarding the merits and shortcomings of the so-called linear model (in which science supposedly "leads" to technology) stem from the narrow and possibly anachronistic definitions of the concept of useful knowledge. In addition to what the eighteenth century called "natural philosophy," it consisted of catalogs of facts, based on experience and experiment rather than on understanding or careful analysis and testing. Many of these facts were organized compilations about what worked: the right mixture of materials, the right temperature or pressure in a vessel, the correct fertilizer in a given type of soil, the optimal viscosity of a lubricant, the correct tension on a piece of fabric, the shortest way to sail across the sea while using the right trade winds and avoiding reefs, and not-so-basic facts of nature used in productive activities from medicinal herbs to cattle breeding to glass blowing to marling. It involved not only the work of people whom we regard today as scientists but also those who collected data and practices—botanists, zoologists, geographers, mineralogists, instrument-makers, and other highly skilled artisans—and placed this knowledge in the public realm. For that reason I prefer the much wider category of *propositional knowledge*.[13]

THE ENLIGHTENMENT AND EIGHTEENTH-CENTURY TECHNOLOGY

The Enlightenment of the late seventeenth and eighteenth centuries bridges the Scientific and the Industrial Revolutions. Definitions of this amorphous and often contradictory historical phenomenon are many, but

[12] Price, "Notes towards a Philosophy." Rosenberg, *Perspectives* and "How Exogenous is Science?"

[13] For more details, see Mokyr, *Gifts,* chap. 2, and "Long-term Economic Growth."

for the purposes of explaining the Industrial Revolution we need only to examine a slice of it, which I have termed the Industrial Enlightenment—a belief in the possibility and desirability of economic progress and growth through knowledge.[14] The idea of *improvement* involved much more than economic growth or technological change; it included moral and social improvement, alleviating the suffering of the poor and the unfortunate, and more generally such matters as justice and freedom. Yet the idea that production could be made more efficient through more useful knowledge gradually gained acceptance. Scotland, again, showed the way, but the idea diffused throughout Britain and the Western world.[15]

It surely is true that not all Enlightenment philosophers believed that material progress was either desirable or inevitable, or were persuaded that the rise of a commercial and industrial society was a desirable end. And yet the cultural beliefs that began to dominate the elites of the eighteenth-century West created the attitudes, the institutions, and the mechanisms by which new useful knowledge was created, diffused, and put to good use. Above all was the increasingly pervasive belief in the Baconian notion that we can attain material progress (that is, economic growth) through controlling nature, and that we can only harness nature by understanding her in order, as he himself put it, to bring about "the relief of man's estate." Francis Bacon, indeed, is a pivotal figure in understanding the Industrial Enlightenment and its impact. "Lord Bacon," as he was referred to by his eighteenth-century admirers, was cited approvingly by many of the leading lights of the Enlightenment, including Diderot, Lavoisier, Davy, and the astronomer John Herschel.[16] Modern scholars seem agreed: Bacon was the most influential mind to regard knowledge as subject to constant growth,

[14] One of the most cogent statements is by McNeil, *Under the Banner*, pp. 24–25, who notes the importance of a "faith in science that brought the legacy of the Scientific Revolution to bear on industrial society . . . it is imperative to look at the interaction between culture *and* industry, between the Enlightenment and the Industrial Revolution." As Spadafora has noted, the belief in the possibility (if not the inevitability) of progress was necessary if the West was to actually experience anything like it. Spadafora, *Idea of Progress*.

[15] The Scottish philosopher George Campbell (1719–1796) noted for example in 1776 that "for some centuries backwards, the men of every age have made great and unexpected improvements on the labours of their predecessors. And it is very probable that the subsequent age will produce discoveries and acquisitions which we of this age are as little capable of foreseeing as those who preceded us in the last century were capable of conjecturing the progress that would be made in the present" (cited by Spadafora, *Idea*, p. 56).

[16] Sargent, ed., *Francis Bacon,* pp. xxvii–xxviii. In a wonderful piece of doggerel entitled *Ode to the Royal Society,* written by the now (deservedly) neglected poet Abraham Cowley (one of the Society's co-founders) and reprinted as a preface to Thomas Sprat's celebrated *History of the Royal Society of London*, the gratefulness of the scholars of the time to Bacon was well-expressed: "From these and all long Errors of the Way; In which our wandring Predecessors went; And like the old Hebrews many Years did stray; in Desarts but of small Extent; Bacon, like Moses, led us forth at last; The barren Wilderness he past; Did on the very Border stand; of the blest promis'd Land; And from the Mountain's Top of his exalted Wit; Saw it himself and shew'd us it."

as an entity that continuously expands and adds to itself.[17] As such his influence helped inspire the Industrial Enlightenment.[18] The understanding of nature was a collective project in which the division of knowledge was similar to Adam Smith's idea of the division of labor, another enlightenment notion. Smith realized that such a division of knowledge in a civilized society "presented unique and unprecedented opportunities for further technical progress."[19] The more pragmatically inclined thinkers of the Industrial Enlightenment concurred.[20] Bacon's idea of bringing this about was through what he called a "House of Salomon"—a research academy in which teams of specialists collect data and experiment, and a higher level of scientists try to distill these into general regularities and laws. Such an institution was the Royal Society, whose initial objectives were inspired by Bacon.[21] A finer and more extensive division of knowledge could not have been attained without improved access that made it possible to share the knowledge, and then apply and adapt it to solve technical problems. Access to useful knowledge created the opportunities to recombine its components to create new forms that would expand the volume of knowledge at an ever faster rate. Bacon, indeed, placed a high value on compiling inventories and catalogues of *existing* knowledge and techniques; some of these ideas are reflected in the interest the Royal Society displayed in the

[17] As always, there were earlier expressions of such ideas, not always wholly acknowledged by Bacon. One example is the sixteenth-century French theologian Pierre de la Ramée (Peter Ramus), with whom Bacon would have agreed that "the union of mathematics and the practice of scholarly arts by artisans would bring about great civic prosperity" (Smith, *Business*, p. 36).

[18] Farrington, *Francis Bacon*. Vickers, "Francis Bacon." Bacon's influence on the Industrial Enlightenment can be readily ascertained by the deep admiration the *encyclopédistes* felt toward him, exemplified by a long article on *Baconisme* written by the Abbé Pestre and the credit given him by Diderot himself in his entries on *Art* and *Encyclopédie*. The *Journal Encyclopédique* wrote in 1756 "If this society owes everything to Chancellor Bacon, the philosopher does not owe less to the authors of the *Encyclopédie*" (cited by Kronick, *History*, p. 42). The Scottish Enlightenment philosophers Dugald Stewart and Francis Jeffrey agreed on Baconian method and goals, even if they differed on some of the interpretation (Chitnis, *Scottish Enlightenment*, pp. 214–15). A practical enlightenment scientist such as Humphry Davy had no doubt that Bacon was ". . . was the first philosopher who laid down plans for extending knowledge of universal application; who ventured to assert, that all the science could be nothing more than expressions or arrangements of facts . . . the pursuit of the new method of investigation, in a very short time, wholly altered the face of every department of natural knowledge. Davy, "Sketch," pp. 121–22. Across the channel, the French minister of the Interior, Nicolas-Louis François de Neufchâteau invoked the spirit of Francis Bacon when opening the 1798 French industrial exhibition. See Jacob, "Putting Science."

[19] Rosenberg, "Adam Smith," p. 137.

[20] A typical passage in this spirit was written by the British chemist and philosopher Joseph Priestley: "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, *Essay,* p. 7.

[21] McClellan, *Science Reorganized*, p. 52.

"useful arts" in its early years.[22] In subsequent decades, the Royal Society accepted amateurs and dilettantes and thus became less of a pure "Baconian" institution than the French *Académie Royale*.

Of course, the eighteenth century still saw a lot of efforts that were purely epistemic or metaphysical in motivation, but the emphasis was slowly changing. The message that the Industrial Revolution inherited from the seventeenth century concerned the very purpose and objective of propositional knowledge. The result was a change in the *agenda* of research, in which the "useful arts" began to assume an equal, and eventually dominant, place alongside the liberal arts. This "Baconian Program" assumed that the main purpose of knowledge was to improve mankind's condition rather than the mere satisfaction of that most creative of human characteristics, curiosity, or the demonstration of some metaphysical point, such as illustrating the wisdom of the creator.[23] Studying and extending useful knowledge, it was increasingly felt, was respectable and suitable work for a gentleman.[24] Natural philosophy, its prestige hugely enhanced by the insights of Newton, was marketed as being useful to economic improvement.[25] Farmers, manufacturers, sailors, engineers, merchants, miners, bleachers, and army officers asked questions, and the community of learned persons, the *savants*, were more and more pressured to provide them with answers. 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."[26] The great Lavoisier worked on assorted applied problems, including as a young man on the chemistry of gypsum and the problems of street lighting. Perhaps no area of propositional knowledge showed as much promise to application as mathematics, which made enormous strides after the seminal works of Descartes, Huygens, Newton, and Leibniz. Mathematical techniques following the development of calculus were applied to questions of motion and the challenges of mechanics, although these were initially not

[22] As Musson and Robinson stress in *Science and Technology*, p. 16, "Bacon's influence can be perceived everywhere among men of science in the seventeenth and eighteenth centuries, constantly encouraging them to comprehend workshop practices."

[23] Calvin in the sixteenth century still followed St. Augustine's condemnation of curiosity as a "vanity." By way of contrast, in the 1660s, Thomas Sprat felt that gentlemen were suitable to research precisely because they were "free and unconfined."

[24] Thus in 1710 the *Tatler* wrote that "It is the duty of all who make philosophy the entertainment of their lives, to turn their thoughts to practical schemes for the good of society, and not pass away their time in fruitless searches which tend rather to the ostentation of knowledge than the service of life." Cited by Shapin, "Scholar," p. 309. In a similar vein, *The Gentleman's Magazine* wrote in 1731 that "our knowledge should be in the first place that which is most useful, then that which is fashionable." Cited by Burke, *Social History*, p. 111.

[25] Cohen, "Inside Newcomen's," p. 127, points out that the Baconian ideology "went under the sainted name of Newton."

[26] Desaguliers, *Course*, vol. 1, p. iii.

the mechanics of engineers and architects as much as those of "rational mechanics," which analyzed idealized properties, rather than actual day-to-day problems loaded with ugly characteristics such as friction and resistance. Many of the leading *philosophes* of the Enlightenment, including Diderot, were pessimistic of the ability of mathematics to advance beyond its current state and contribute much to material progress.[27] Yet mathematicians were often asked to solve practical problems. Leonhard Euler, the most talented mathematician of the age, was concerned with ship design, lenses, the buckling of beams, and (with his less famous son Johann) contributed a great deal to hydraulics.[28] Naturalists and botanists, in very different ways, were equally regarded as contributing to the wealth of their nations. Linnaeus's belief that skillful naturalists could transform farming was widely shared and inspired the establishment of agricultural societies and farm improvement organizations throughout Europe. By the second half of the eighteenth century, botany, horticulture, and agronomy were working hand-in-hand through publications, meetings, and model gardens to introduce new crops, adjust rotations, improve tools, and better management.[29]

Many of the answers that mathematicians and natural philosophers gave to engineers, industrialists, and farmers were, of course, useless, misleading, or wrong. The eighteenth century was nothing at all like a steady progress of better understanding of nature and its application to agriculture and manufacturing. The alleged "usefulness" of knowledge was often an attempt by scholars to secure financial support and patronage from wealthy individuals and official sponsors.[30] But no matter how self-serving and pre-

[27] Furbank, *Diderot*, p. 110. Hankins, *Science*, p. 45. Hankins add that "Diderot was wrong . . . in the years between 1780 and 1840 . . . mathematics and mechanics found a place precisely where Diderot thought they had no place."

[28] See above all, Reynolds, *Stronger*, pp. 233–50. Another example of such an application of mathematical knowledge to a mundane problem is Colin MacLaurin's ingenious solution (1735) to the problem of measuring the quantity of molasses in irregularly shaped barrels by the use of classical geometry. Not only did he solve the rather difficult mathematical problem with uncommon elegance, he also provided simple formulas, tables, and algorithms for the customs officers, that were used for many years. See Grabiner, "Some Disputes," pp. 139–68.

[29] One source of confirmation of the belief in the possibility of economic progress may have been perceptions of agricultural progress. As John Gascoigne has recently noted, "as the land bore more, better, and increasingly diversified fruits as a consequence of patient experiment with new techniques and crops, so, too, the need to apply comparable methods to other areas of the economy and society came to seem more insistent." Gascoigne, *Joseph Banks*, p. 185.

[30] A good early example of such hope was the work of the Scottish botanist and physician, Sir Robert Sibbald (1641–1721), whose widespread interests, extensive correspondence network, and continental education were harbingers of things to come in the eighteenth century. Sibbald was extremely active in reforming the University of Edinburgh and helped establish the Royal College of Medicine as well as an early botanical garden in town. Yet as Paul Wood remarks, much of Sibbald's work failed to bear fruit in his lifetime, and his dream to turn learning into material benefit was largely disappointed in his lifetime. See Wood, "Science." For a general discussion of the

tentious the claims of those who controlled propositional knowledge were, the Industrial Enlightenment did not waver in its belief that economic growth through better and more knowledge was possible. Progress through more and better knowledge also had moral and political implications; it was believed that better-informed and more enlightened individuals would be more ethical and better-behaved citizens. "Useful knowledge" in the eighteenth century thus meant something more than it does to our wiser and sadder age.

ACCESS COSTS: SOME REFLECTIONS

The Industrial Enlightenment was in part about the expansion of useful knowledge. Knowledge exists in the final analysis within the mind of an individual, but for it to be socially productive it needs to be shared and distributed. If a vital piece of knowledge is discovered but only one individual possesses it and keeps it secret, it is by definition part of social knowledge, but has little economic value. What counted for useful knowledge to play a role in generating economic growth was therefore *access costs*, the marginal cost involved in acquiring knowledge possessed by someone else in society. The concept is in line with recent thinking about the Enlightenment which regards it above all "as a system of communication creating a public of rational individuals."[31] The economic significance of access costs has three dimensions. The first is obvious: access made it possible for producers to learn of best-practice techniques and emulate them. Needless to say, access costs are not the only wedge between best- and average-practice techniques, but it is safe to assume that ignorance will make such wedges both larger and more permanent. Secondly, technological progress depended on the knowledge of other techniques already in use. As has often been noted, much invention took the form of the "recombination" of existing techniques.[32] Moreover, technological progress often depended on "analogical" thinking, in which inventors, consciously or subconsciously, transform an idea they have already seen into something novel.[33] Furthermore, knowledge of what techniques exists will alert original and creative individuals to gaps and opportunities in the existing set of techniques, and prevent potential inventors from misspending their resources by reinvent-

quest for patronage through claims for usefulness, see especially, Spary, *Utopia's Garden*, p. 127.

[31] Censer, "Journals," p. 311, though he should have added "informed" to the "rational."

[32] The classic example of such an invention during the Industrial Revolution is surely Cort's patent for the second half of his puddling and rolling process, in which the common rolling mill was used to weld together pieces of scrap iron at a sufficiently high temperature. His invention "clearly inspired" a naval contractor named William Forbes who used grooved rollers to produce improved copper bolts for naval ships (Harris, "Copper," p. 183). For a theoretical discussion of recombination in technological change, see Weitzman, "Hybridizing," pp. 207–13.

[33] McGee, "Rethinking Invention."

ing the wheel. Thirdly, as I have stressed in my *Gifts of Athena*, lower access costs made it possible for inventors to tap the propositional knowledge on which the new technique rests—insofar as such knowledge was available and effective.[34] Understanding *why* and *how* a technique works at some level of generality made it easier to clean up bugs, adapt it to new uses and different environments, and unleashed the cumulative stream of microinventions on which nineteenth-century productivity growth rested. It streamlined the process of invention by reducing the likelihood of blind alleys such as searches for perpetual motion machines and the like. All of these suggest that the easier the access to existing propositional knowledge and to practices in use, the more likely inventions were to emerge and result in sustained economic growth. Contemporaries became slowly aware of the possibilities of bringing to bear science on production technology.[35] As one assiduous collector of facts remarked in 1772, "before a thing can be *improved* it must be *known*, hence the utility of those publications that abound in fact either in the offer of new or the elucidation of old ones."[36] Whether in agriculture, pottery, steam-engine construction, or chemical industry, leading manufacturers eagerly sought and found the advice of scientists. In and of itself this does not prove that this knowledge was instrumental in technical advances and productivity growth, as these progressive industrialists may have been successful for other reasons. But in the nineteenth century such input becomes more and more prominent.[37]

The level of access costs can be decomposed into four separate components. First, there was the cost involved in establishing that this knowledge actually existed, that is, that there was at least one individual in society who possessed it. Second, there was the cost of finding out who the lowest-cost supplier of this knowledge was and where it could be found. Third, there was the actual cost of acquiring it, which could range from a simple search through a library or catalog to the need of reading a scien-

[34] I use the term "effective" rather that "correct" because terms such as "true" or "correct" are irrelevant and inappropriate here. The best we can do is to say that a piece of knowledge held in the past was "right" or "wrong" in the sense that it is inconsistent with our beliefs. By "effective" I mean such knowledge on which certain techniques rest that perform better than techniques based on some other base according to some prespecified criterion. For instance, bloodletting might have been effective simply because it did help patients if only through a placebo effect.

[35] As Voltaire noted in his *The Age of Louis XV*, written late in his life in 1770: "pure natural philosophy has illustrated the necessary arts; and these arts have already begun to heal the wounds of the state caused by two fatal wars. Stuffs manufactured in a cheaper manner, by ingenuity of the most celebrated mechanics" (Vol. 2, pp. 369–70).

[36] Young, *Political Essays*, p. v., emphasis in original.

[37] One telling example is Neilson's hot blast (1828), a fuel-saving innovation from the "second stage" of the Industrial Revolution. Neilson had learned of Gay-Lussac's calculation of the rate of expansion of oxygen and nitrogen between 0^o and 80^0 C and used laboratory experiments to persuade Scottish ironmasters to apply it, which proved "the salvation of the Scottish iron industry" (Clow and Clow, *Chemical Revolution*, p. 356).

tific article, visiting a site, or hiring a consultant or expert who could convey it. Fourth, there was the cost of verifying the knowledge and establishing the extent of its "tightness," that is, to what extent was this a consensus view among the experts or authorities on certain propositions and how certain were they of its truthfulness?

What determined access costs? One obvious determinant is technological: how costly was it to code, store, transmit, and receive useful knowledge, what was the best-practice technology through which it was transmitted, and in what language and terminology was it expressed? Another is social and cultural: to what extent were individuals who made a discovery willing to share such useful knowledge (for example as part of "open science" that awards credit for priority), and allow inventions to be used freely (for instance in processes of collective invention or "open source" development)? Did organizations exist that channeled knowledge from those who knew useful things to those who could and were willing to exploit such knowledge? Finally, there are economic factors: did markets for useful knowledge exist? Economists know that such markets (and the intellectual property on which they rest) will be deficient and incomplete, yet *some* of them clearly did exist and others emerged during the Industrial Revolution.

ACCESS COSTS: TECHNICAL FACTORS

The decline in access costs in the century or so before the Industrial Revolution cannot be attributed to a single factor. There is no question that the costs of transmitting information was declining already before the arrival of the railroad. Abstracting from homing pigeons and the semaphore telegraph, knowledge moved as fast and as far as people did. People and carriages carried books, periodicals, and other storage devices. All the same, much of the knowledge that counted was not written down or depicted in the (increasingly detailed and sophisticated) technical drawings of the age, but embodied in implicit forms we would call "skills," "dexterity," and other synonyms for what is known as tacit knowledge. The ratio of codified knowledge to tacit knowledge was itself a function of the technology and costs of codification and the payoff to efforts to do so, although tacit knowledge inevitably remained an essential part of knowledge.[38] Access to knowledge thus depended not only on written records, but also on personal transmission and training. Much of the tacit and practical useful knowledge in eighteenth-century Europe moved about through

[38] For a more detailed analysis of the economics of tacit knowledge, see Cowan and Foray. "Economics," pp. 595–622.

itinerant skilled artisans who taught the tricks of their trade to local craftsmen. Beyond that, the normal human proclivities for observation and imitation did their work.[39] Industrial espionage, both within an economy and across borders, became an important part of technological diffusion.[40] In Enlightenment Europe, people—including skilled craftsmen—moved about more often and further than ever before, despite the undeniable discomforts of the road. Although the great breakthroughs in transport technology were still in the future, the decline in the cost and speed of moving about in Europe in the eighteenth century are too well documented to require elaboration here.[41] Transportation improvements also sped up the mail; a great deal of scientific communication depended on personal correspondence between individuals.

The eighteenth century also witnessed the improvement of the transfer of formerly tacit knowledge. Part of it was simply the improvement of the language of technology: mathematical symbols, standardized measures, and more universal scales and notation added a great deal to the ease of communication of codified technological information. Diagrams and illustrations became more sophisticated.[42] Above all, there was printing, but in and of itself printing was not decisive, or else the Industrial Revolution might have occurred in the sixteenth century. Paper had been introduced into Europe in the thirteenth century, and as an access-cost and storage-cost reducing material it must have had few substitutes. The paper industry grew remarkably in the seventeenth century, culminating in the invention

[39] Harris, "Skills." Epstein, "Knowledge Sharing," especially pp. 15–20. Eighteenth-century Europe was crisscrossed by a variety of technological informants and spies such as Gabriel Jars (studying metalmaking) and Nicolas Desmarest (papermaking) (Gillispie, *Science . . . End of Old Regime,* pp. 429–37, 444–54). For a discussion of the importance of geographical mobility on the diffusion of artisanal skills in Italy, see Belfanti, "Guilds." The effect of traveling was also notable in the improved access to agricultural knowledge, as attested to by the many Frenchmen who visited Britain after 1750 to study farm methods and techniques. See Bourde, *Influence.*

[40] Harris, "Industrial Espionage," pp. 164–75, and *Industrial Espionage.* British legislation to prevent the outflow of skilled craftsmen and certain kinds of machinery were in the long run doomed to failure, though it is hard to disagree with Harris's assessment that they raised access costs and had a retardative effect on the diffusion of technology.

[41] In Britain, better-built roads and coaches sharply reduced internal travel time in the eighteenth century: the coach from London to Edinburgh still took 10–12 days in the mid 1750s, whereas in 1836 (just before being replaced by a railroad) it could cover the distance in 45.5 hours. In France, travel times were halved or better on many routes between 1765 and 1785. See data reported by Szostak, *Role*, p. 70.

[42] Thomas Newcomen surely must have seen Papin's sketches of his models of proto-engines and pumps, published in various issues of *Philosophical Transactions* between 1685 and 1700. One example of a book that codified a great deal of formerly tacit knowledge was Bernard de Bélidor's famed *Architecture Hydraulique*, published in four volumes in 1737. It discussed almost all fields of civil engineering, and the great British engineers John Smeaton, John Rennie, and Thomas Telford all owned copies. Charles Plumier (1646–1704) wrote a book on the art of using a lathe (*l'Art de Tourner*), which—whether of use to craftsmen or not—was sufficiently regarded to be translated into Russian, the translation attributed to Emperor Peter the Great himself.

of the *Hollander* (1670), a device that applied wind- or water power to the difficult process of ripping up the rags needed for pulping.[43] The effect of printing and paper was, as Eric L. Jones has noted, constrained in that only widespread literacy could realize its full effect throughout society. It also mattered, of course, whether the literate actually read, and what kind of texts they chose. In Enlightenment Europe, the printing press finally lived up to its full potential. It may still have been that, as Jones points out, "published ideas flowed through narrow channels bounded by limited literacy and unlimited poverty," and that the bulk of the population had little or no access to libraries and could not afford to buy books or (highly taxed) newspapers. But technical knowledge had a way of seeping through to those who needed it and could find a use for it.[44] Reading became increasingly common, as literacy rates edged upward and books became cheaper and more widely available through lending libraries and the reading rooms attached to learned societies and academies. The first free public library in Britain, Chetham's in Manchester, was founded in 1653 and prospered in the eighteenth century.[45] Coffee houses and booksellers often offered magazines to be browsed by customers.[46] Many of the scientific and scholarly societies that emerged in the eighteenth century built up their own libraries. The idea was to make useful knowledge accessible. Furthermore, in the century between Newton's *Principia* and Lavoisier's *Traité Elementaire* Latin disappeared as the language in which books were published.[47]

A telltale sign of the changing age were the scientific and other technical magazines that began appearing all over Europe. Many of these periodicals were derivative popularizations and intended to summarize and review the existing literature, and thus directly reduced access costs even if their respect for intellectual property left a lot to be desired. To be sure, only a minority of the population read, and that of those the bulk read novels, romantic potboilers turned out by hacks in what Robert Darnton has called "Grub Street," scandalous pamphlets and religious tracts. Books on

[43] For a study of Pierre Montgolfier, one of the most progressive paper manufacturers of eighteenth-century France, see Rosenband, *Papermaking*.

[44] Jones, "Culture," p. 13.

[45] Musson and Robinson, *Science and Technology,* p. 113. In 1697 the rev. Thomas Bray [1697, (1967)] called for 400 lending libraries to be established throughout Britain, believing that making knowledge more accessible would "raise a Noble Spirit of Emulation in those Leaned Societies and would excite more of the members thereof to exert themselves in being serviceable to the world" (p. 11).

[46] See Outram, *Enlightenment*, p. 21.

[47] The Swedish metallurgist Tobern Bergman published his major work, *De Praecipitatis Metallicis* (a major theoretical essay on the nature of steel) in Latin as late as 1780. An English translation, by no less a scholar than William Withering, a founding member of the Lunar Society, came out in 1783.

the useful arts, science, and mathematics were without doubt of interest to only a small minority.[48] Even within science, the majority of publications were concerned with the kind of knowledge that was not often directly concerned with the technical problems of the early stages of the Industrial Revolution.[49]

Useful knowledge was thus transmitted in codified form through "storage devices." John R. Harris, an authority on British eighteenth-century technology, has doubted the extent that codified knowledge mattered in the early stages of the Industrial Revolution. As far as skills and workmanship were concerned, it is possible to exaggerate the importance of books and periodicals as means through which technical knowledge was accessed. It surely was less important in the metal trades or mining than in medicine, agriculture, instrument-making, electricity, astronomy, or chemistry. It changed over time, with much of the volume of technical and scientific publishing concentrated in the last third of the eighteenth century.[50] Yet Harris's judgment is also affected by his narrow focus on the transmission of the techniques themselves, without fully realizing that what mattered in many industries is the diffusion of the propositional knowledge on which the techniques rested, so that they could be adapted, refined, and tweaked by the select few who accessed these knowledge bases. Moreover, artifacts and instruments were storage devices as much as descriptions and illustrations. In the eighteenth century, an international market in scientific and industrial instruments had emerged, with British instrument makers buying and selling instruments to and from all over Europe.[51] These instruments were used for scientific experimentation as well as for industrial improvement; in the eyes of the men of the Industrial Enlightenment, there was little difference between the two. Capital goods such as steam engines and spinning machines were moving about, various prohibitions on the export of machinery notwithstanding.

[48] A study of the contents of French private libraries (probably unrepresentative) shows only about 3.2 percent of all books devoted to what we may call useful knowledge, more than half being novels and 32 percent being devoted to history or theology. See Mornet, "Enseignements," p. 457.

[49] The "Natural Science" section of J. D. Reuss's *Repertorium* (Index of scientific literature) published between 1801 and 1821 (covering only a small part of the scientific journals) indicates that astronomy accounted for 19 percent of the scientific papers published between 1665 and 1800 and zoology for 18 percent, whereas mechanics accounted for 4 percent and chemistry for 6 percent. See Gascoigne, *Historical Catalogue*, p. 100.

[50] Harris, "Skills," pp. 21–23. It might be added that Harris writes specifically about mining and coal-using technology, and that outside geology and the adoption of steam-powered pumps, there was actually little technological progress in the mining sector.

[51] Thus the Portuguese instrument maker Jean Hyacinthe de Magellan—who had worked with Priestley in the 1770s—bought thermometers from Wedgwood, and sold the needed instruments to Alessandro Volta. Volta in turn used these to construct his eponymous pile (reputedly upon hints received from William Nicholson in London). See Stewart, "Laboratory," p. 13.

It could be objected that this knowledge, whether codified or tacit, was shared by only a minute percentage of the population. However, the technological thrust during the Industrial Revolution was not the result of the action of the majority of population; in the hurry of the economic history profession to get away from the absurd hero-worship of a few key inventors as having carried the Industrial Revolution, it has tended to go too far in the other direction by asserting that unless much or most of the population had access to technical knowledge, the spread of new techniques was limited. The truth is somewhere in between; it is undeniable that technological progress during the Industrial Revolution was an elite phenomenon, carried not by a dozen or two of big names who made it to the *National Dictionary of Biography*, but by the thousands of trained engineers, capable mechanics, and dexterous craftsmen on whose shoulders the inventors could stand.

Yet when all is said and done, we are talking about thousands, perhaps a few tens of thousands, not hundreds of thousands or millions of people in industrializing Europe; democratic instincts notwithstanding, what the large majority of workers knew mattered little as long as they did what they were told by those who knew more.[52] Technological advance in the period of the Industrial Revolution was a minority affair; most of the entrepreneurs of the time were not like Boulton and Wedgwood and had no knowledge of or interest in science or even innovation, just as most landowners were not improvers. But the dynamics of competition are such that in the long run the few drag along the many.

The exact composition of who these "few" were changed during the period in question. Late in the seventeenth century and in the first decades of the eighteenth, it was clearly the political elite that felt that new knowledge and the rejection of age-old sacred cows were the keys to social progress. Over the eighteenth century, conservative elements slowly gained the upper hand, especially when liberal and progressive elements were allied with both the American rebels and the French Jacobins. Especially in Britain, anti-Enlightenment sentiments flared up in the 1790s. But whatever happened in the center of power in London, it could not stop the Industrial

[52] Adam Smith expressed this kind of elitism in his "Early Draft," in which 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, *Lectures on Jurisprudence*, pp. 569–72. Soame Jenyns, a mid-eighteenth-century writer, advocated ignorance for the poor as "the only opiate capable of infusing the insensibility which can enable them to endure the miseries of poverty and the fatigues of the drudgeries of life." See Jenyns, *Free Inquiry*, pp. 65–66. As Rosenberg points out, such a division of knowledge was increasingly pertinent to a sophisticated ("civilized") society in which specialized "philosophers" would account for technological progress. Compare Rosenberg, "Adam Smith," pp. 134–36.

Enlightenment from spreading into provincial society. In the European provincial societies of Manchester, Liverpool, Newcastle, Leeds, Antwerp, Lyons, Marseilles, Nantes, and Milan, J. H. Plumb has noted, we do not find Diderots and Humes, but neither do we find [reactionary thinkers] such as Samuel Johnson or Edmund Burke. Instead, "we find knots of enlightened men with a passionate regard for empirical knowledge, secular in their intellectual attitudes, although often muddled, uncertain and tentative, with . . . rational and irrational beliefs combined in the same man." Their religious feelings were quite diverse and many thoughtful and well-read minds of the enlightenment still fell for bogus and faddish ideas put out by charlatans.[53] On the whole, not all important eighteenth-century thought was enlightened, and the Enlightenment itself was a complex and often self-contradictory movement in which many different streams competed. Some scholars have found the differences between thinkers *within* the Enlightenment more important than their common denominator.[54] As Plumb put it in his inimitable style, "between the stars of the first magnitude are vast spaces of darkness."[55] Yet these spaces of "darkness" are often revealed, at closer inspection, to be filled with interesting material and some beliefs and axioms that were shared across the regions where the influence of the Enlightenment was palpable. In the end, the belief in advances in knowledge and their capability to improve the human lot was the one intellectual heritage that was critical to material progress.

ACCESS COSTS: CULTURAL AND SOCIAL FACTORS

In addition to the technology of access there was culture. The culture of "open science" that evolved in the seventeenth century meant that observation and experience were placed in the public domain and that credit was assigned by priority. Its openness manifested itself in two dimensions, both in the full disclosure of findings and methods, and in the lack of barriers to entry for competent persons willing to learn the language. Scientific knowledge became a public good, communicated freely rather than confined to a secretive exclusive few as had been the custom in medieval Europe. Openness, as Paul David and others have pointed out, had major benefits in that validation was made easy, duplication reduced, and spill-over effects could be augmented. It increasingly closed down research

[53] Well-known examples were the wondrous Dr. John Brown (1735–1788), whose popularity was based on his insistence that all diseases could be cured by either alcohol or opium, and the notorious fraud Alessandro Cagliostro (1743–1795), who peddled elixirs of youth and love powders to the high and mighty, and whose séances had become the rage of fashionable society in Paris by 1785, until he found himself in the Bastille.

[54] For example, von Hayek, "Legal and Political Philosophy," p. 106.

[55] Plumb, "Reason," pp. 5, 23.

roads that led to cul-de-sacs and bogus knowledge. Magic, occult, mystical beliefs, and simple charlatanry, while still alive and often well in the eighteenth century, found themselves on the defensive against an increasingly skeptical community that demanded to reproduce or refute their results.

Access costs depend crucially on the culture and social customs of useful knowledge. The rhetorical conventions of scientific discourse changed in the seventeenth century. Authority and trust, of course, remained essential to the pursuit of knowledge as they must, but the rules of the discourse and the criteria for "what was (believed to be) true" or "what worked" shifted toward a more empirical and verifiable direction. The community of those who added to useful knowledge demanded that it be tested, so that it could be trusted.[56] Verification and testing meant that a deliberate effort was made to make useful knowledge "tighter" and thus, all other things equal, more likely to be used.[57] This tightness is what makes modern science a strategic factor in economic growth. Inevitably, the skepticism of experts of each others' findings and the careful testing reinforced the trust of the potential users, who could assume that this knowledge had already been vetted by the very best; if it had been accepted by them, the likelihood of an error was minimized.[58] In science, as in commercial transactions, trust is an information-cost saving device and as such was essential if useful knowledge was not only to be diffused but also verified and accepted and—most important for our purposes—acted upon.[59] The sharing of knowledge within "open science" required systematic reporting of methods and materials using a common vocabulary and consensus standards, and was the major component in the decline in access costs, making

[56] Steven Shapin has outlined the changes in trust and expertise in Britain during the seventeenth century, associating expertise, for better or for worse, with social class and locality. Although the approach to science was ostensibly based on a "question authority" principle (the Royal Society's motto was *nullius in verba*—on no one's word), in fact no system of shared useful (or any kind of) knowledge can exist without some mechanism that generates trust. The apparent skepticism with which scientists treated the knowledge created by their colleagues increased the trust that outsiders could have in the findings, because they could then assume—as is still true today—that these findings had been scrutinized and checked by other "experts." See Shapin, *Social History*.

[57] By "tight," I mean knowledge that is believed to be true by a consensus, and that this consensus is based on considerable confidence.

[58] As Hilaire-Pérez put it, "the value of inventions was too important an economic stake to be left to be dissipated among the many forms of recognition and amateurs: the establishment of truth became the professional responsibility of academic science." (Hilaire-Pérez, *Invention Technique*, p. 60).

[59] In the scientific world of the late seventeenth and eighteenth centuries, a network of trust and verification emerged in the West that seems to have stood the test of time. It is well described by Polanyi; the space of useful knowledge is divided in small neighboring units. If an individual B is surrounded by neighbors A and C who can verify his work, and C is similarly surrounded by B and D and so on, the world of useful knowledge reaches an equilibrium in which science, as a whole, can be trusted even by those who are not themselves part of it. Polanyi, *Personal Knowledge,* pp. 216–22.

propositional knowledge, such as it was, available to those who might find a use for it.

This trend was reinforced by a redefinition of fact and experience: seventeenth-century and early enlightenment scientific thought became more interested in cataloguing specific events, to be reassessed and reformulated into general principles based in the best Baconian tradition, on hard empirical facts and the results of experiment. Yet there are facts and there are facts. In the second half of the eighteenth century, those in charge of augmenting the set of propositional knowledge increasingly relied on quantification and formal mathematical methods. The increasing reliance on mathematics and graphical representation in the writing of technical works supported this need for precise and effective communication. As Robin Rider puts it, "mathematics was eminently rational in eighteenth century eyes, its symbols and results were truly international . . . in an age that prized the rational and the universal, mathematics . . . offered inspiration and example to the reformers of language."[60] Formal methods and quantification are access-cost reducing devices, in that they are an efficient language to communicate facts and relationships, and that the rules are more or less universal (at least within the community that counted for the processing and application of useful knowledge). Computation and formal methods were necessary because they were an efficient way of communicating and because they lent themselves more readily to falsification. A rhetoric of precision, through meticulous procedures and sophisticated equipment, emerged and facilitated scientific consensuses, if not always in straightforward manner.[61] J. L. Heilbron submits that in the seventeenth century most of "learned Europe" was still largely innumerate, but that in the second half of the eighteenth century propositional knowledge, from temperature and rainfall tables to agricultural yields, the hardness and softness of materials, and economic and demographic information was increasingly presented in tables and expected its readers to be comfortable with that language (or at least be willing to learn).[62] Tables not only made the presentation of information more efficient, they organized and analyzed it by forcing the author to taxonomize the data. A booklet such as Smeaton's famous *Treaty on Water and Wind Mills* used tables lavishly to report his experiments, but already four decades earlier, in 1718, Henry Beighton had published a table entitled *A Calculation of the Power of the Fire (Newcomen's) engine shewing the Diameter of the*

[60] Rider, "Measure," p. 115.

[61] The triumph of Lavoisier's chemistry over its British opponents in the later 1790s is a good example. See Golinski, "Nicety."

[62] Heilbron, "Introductory Essay," p. 9. These methods soon were applied to mundane purposes. An example is Dougharty, *General Gauger*. The first half or so of the book lays out arithmetic manipulations, starting from the basics.

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.[63] Tables of astronomical, legal, historical, literary, and religious information appeared in many eighteenth-century books, but some of it was practical and mundane. John H. Desaguliers in 1734 published a (bi-lingual) set of 175 tables from which jewelers could determine the value of diamonds.[64] Later in the eighteenth century tables were complemented by graphs, and the growing sophistication of information was enhanced by visual means. William Playfair pioneered the display of data in graphical form, defending their use explicitly on the basis of a reduction in access costs.[65] This idea caught on but slowly, and oddly enough faster on the Continent than in Britain, which seems on the whole to have preferred tables.[66] That even with formal notation and well-organized data there will still be plenty of ambiguity left is something that most economists—and surely all economic historians—are all too keenly aware of.

Precisely because the Industrial Enlightenment was not limited to being a national or local phenomenon, it became increasingly felt that differences in language and standards were an impediment and increased access costs. Watt, James Keir, and the Derby clockmaker John Whitehurst, worked on a system of universal terms and standards that would make French and British experiments "speak the same language."[67] In the eighteenth century access costs fell in part because national and geographic barriers were easily crossed.[68] The Enlightenment movement as a whole was cosmopolitan, with the typical scientist or philosopher more a citizen of the Republic of Letters than of his own country.[69] Many of the central figures of the Indus-

[63] Smeaton, *Experimental Enquiry*. Beighton's Table is reproduced in Desaguliers, *Course of Experimental Philosophy*, p. 535. Desaguliers remarked that "Mr. Beighton's table agreed with all the experiments made ever since 1717." For more details on Beighton, a remarkable early example of the Industrial Enlightenment, see Stewart, *Rise*, pp. 242–51.

[64] Desaguliers, *Jewellers Accounts*.

[65] Playfair, *The Commercial and Political Atlas*. "As knowledge increases amongst mankind, and transactions multiply, it becomes more and more desirable to abbreviate and facilitate the modes of conveying information." Cited by Headrick, *When Information*, p. 127. This text does not appear in the 1786 original edition. Playfair's book was concerned with economic data, not science and technology.

[66] James Watt, Playfair's employer, advised him "that it might be proper to give in letter press the Tables from which the Charts have been constructed." Cited by Spence, "Invention," p. 78.

[67] Uglow, *Lunar Men,* p. 357.

[68] For an excellent discussion of the growing mobility of scientific and technological knowledge in the eighteenth century, see Inkster, "Mental Capital."

[69] Darnton, "Unity." The idea of the *Respublica Litteraria* goes back to the late middle ages, and by the eighteenth century had extended to mechanical and technical knowledge. John R. Harris has noted that as early as the 1720s the development of the early steam engine was the center of intense interest in the European scientific community, and "international intelligence about the engine diffused with great speed, the speed of correspondence between the scientific luminaries of Europe of that period." See Harris, *Industrial Espionage*, p. 296.

trial Enlightenment were well traveled, none more than Franklin and Rumford, and realized the importance of reading in foreign languages (language difference is a component of access costs).[70] Books on science and technology were translated quickly, even when nations were at war with one another. P. J. Macquer's encyclopedic textbook on chemistry was translated (with considerable additions) by James Keir, a member of the Lunar society, and the works of Lavoisier and Berthollet were translated in Britain within a short time of their first appearances. The British knew all too well that Continental chemists were superior to their own. In return, the French translated scientific works published in Britain, and here too, the translators were often leading experts themselves, such as the Comte de Buffon translating Stephen Hales's influential *Vegetable Staticks* in 1735 and John T. Desaguliers's translating the leading Dutch Newtonian Willem's Gravesande's *Mathematical Elements of Natural Philosophy* (1720), studied later by James Watt (whose father owned the book). Chaptal's *Elements of Chemistry* (1795) was translated into English by William Nicholson, a distinguished chemist.[71] Honor and prestige crossed national boundaries as easily as knowledge. Lavoisier was a fellow of the Royal Society, and corresponded with, among others, Josiah Wedgwood about the use of refractory clays.[72] In 1808 James Watt, Edward Jenner, and the chemist Richard Kirwan were elected foreign associates of the French Academy of Sciences (then known as the *Institut National*), war or no war. Statements such as that knowledge was supranational and that "the sciences were never at war" (as Lavoisier claimed in 1793) are of course an overidealization. Reality, especially after 1793, deviated from the ideals of the Enlightenment, and political and military considerations increasingly got in the way of the free flow of useful knowledge.[73] Useful knowledge, it was realized, could be valuable to the state when engaged in combating another.

Access costs consisted in great measure of knowing what was known, and to facilitate access, knowledge had to be classified. This turned out to be an involved project, and much intellectual capital was spent on taxon-

[70] Robert Hooke taught himself Dutch to read Leeuwenhoek's famous letters on microscopy, and a century later John Smeaton taught himself French to be able to read the papers of French hydraulic theorists such as de Parcieux and traveled to the Netherlands to study their use of wind power firsthand.

[71] Uglow, *Lunar Men*, p. 27. The movement of translations was symmetrical. In 1780 a French publisher published a whole bundle of *Ouvrages sur l'économie politique et Rurale, traduit de l'Anglais* including work by Arthur Young and John Arbuthnot (who had written an important work on ploughs). Bourde, *Influence*, p. 97. In agriculture, as Gillispie correctly points out, the impact of such information flows "beyond the circle of persons who wrote, printed and read the books," was probably small. See Gillispie, *Science . . . End of Old Regime*, p. 367.

[72] Schofield, *Lunar Society*, p. 378.

[73] de Beer, *Sciences,* passim.

omy and the organization of knowledge.[74] Access to knowledge required search engines. The new search engine of the eighteenth century was the encyclopedia, exploiting that miracle of organizational technology, alphabetization. To be sure, Diderot and d'Alembert's *Encyclopédie* did not augur the Industrial Revolution, it did not predict factories, and had little or nothing to say about mechanical cotton spinning equipment or steam engines. It catered primarily to the landowning elite and the bourgeoisie of the *ancien régime* (notaries, lawyers, local officials) rather than specifically to an innovative industrial bourgeoisie, such as it was. It was, in many ways, a conservative document.[75] Moreover, the idea of such a search engine was not altogether new, and attempts to sum up all that is known in some fashion can be found in China and in medieval Europe. However, the drive to organize knowledge in a way that made it accessible at a high level of detail yet easy to use was very much a product of the eighteenth century.[76] The *Encyclopédie* and similar works of the eighteenth century symbolized the very different way of looking at technological knowledge: instead of intuition came systematic analysis, instead of tacit dexterity came an attempt to attain an understanding of the principles at work, instead of secrets learned from a master came an open and accessible system of training and learning. It also insisted on organizing knowledge in user-friendly compilations, arranged in an accessible way, and although subscribers may not have been mostly artisans and small manufacturers, the knowledge contained in it dripped out and trickled down through a variety of leaks to those who could make use of it.[77] Encyclopedias allowed not only for faster searches, but also underlined the agnosticism of the project to biased taxonomies of knowledge. While it may be an overstatement that they were a starting point toward a new concept of knowledge, as pragmatic and heuristic documents they reflected an intellectual innovation that deliberately sought to reduce access costs.[78]

Furthermore, then as now, works that have an "encyclopedic" nature are instinctively trusted. It is believed—perhaps too optimistically—that such synthetic works reflect authority and best-practice knowledge, and that any statements reflecting baseless speculation and personal bias have been ex-

[74] Burke, *Social History*, chap. 5.

[75] Darnton, *Business*, p. 286.

[76] Heilbron, "Introductory Essay," p. 20, notes that Diderot and d'Alembert were but indolent in comparison with the massive (64 volumes) work published by J. H. Zedler, *Grosses vollständiges Universal-Lexikon aller Wissenschafte und Künste*, published 1732–1754.

[77] Pannabecker 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. Pannabecker, "Diderot," pp. 6–22, and "Representing Mechanical Arts."

[78] Broberg, "Broken Circle," pp. 45–71.

cised by conscientious encyclopedia editors. As such, the emergence of encyclopedias as an accessible source of useful knowledge reduced access costs on another front, namely the costs of verification. Many other works of useful knowledge were sponsored by the French Royal Academy, the British Royal Society, or similar formal institutions. Such quasi-official imprimaturs were intended to make them look more believable and tighter.[79] The age also witnessed the rise of bibliographical guides and handbooks, that helped readers find their way to the knowledge they sought.

Encyclopedias and "dictionaries" were supplemented by a variety of textbooks, manuals, compendia, gazettes, and compilations of techniques and devices that were in use somewhere, none more detailed than the over 13,000 pages of the 80 volumes of the *Descriptions des Arts et Métiers* compiled in France before the Revolution—in Gillispie's judgment the "largest body of technological literature ever produced."[80] Much more modest and affordable were the multitudinous "dictionaries" of useful arts published all over Europe.[81] In agriculture, meticulously compiled data collections looking at such topics as yields, crops, and cultivation methods were common.[82] Engineering manuals, meticulous descriptions of various "useful arts" were published, translated, pirated, and—one presumes—read on a wider scale than ever before. One of the most impressive and best-organized of such textbooks was P. J. Macquer's *Dictionnaire de Chimie* published in 1766 and, as noted, translated into English in 1771 by

[79] The "Philosophical Transactions" published by the Royal Society and the "Histoire et Mémoires" published by the *Académie Royale des Sciences* were among the most influential publications of their time. They were routinely reported on in the wide-circulation *Gentleman's Magazine* and abridged, abstracted, and translated all over the Continent.

[80] Cole and Watts, *Handicrafts*. Gillispie, *Science . . . End of Old Regime*, p. 344.

[81] For instance, Jaubert, *Dictionnaire Raisonné*; Hall, *New Royal Encyclopædia*; and Society of Gentlemen, *New and Complete Dictionary*.

[82] William Ellis's *Modern Husbandman or Practice of Farming* (1731) gave a month-by-month set of suggestions, much like Arthur Young's most successful book, *The Farmer's Kalendar* (1770). Summaries of this information often took the form of frequently updated dictionaries and compendia, such as Society of Gentlemen, *Complete Farmer* first published by the Society of Arts in 1766. Most of these writings were empirical or instructional in nature, but a few actually tried to provide the readers with some systematic analysis of the principles at work. One of those was Francis Home's *Principles of Agriculture and Vegetation* (1757). Some of the great private data collection projects of the time were Arthur Young's famed *Tours* of various parts of England and William Marshall's series on *Rural Economy* (Goddard, "Agricultural Literature"). They collected hundreds of observations on farm practice in Britain and the continent, although at times Young's conclusions were contrary to what his own data indicated. See Allen and Ó Gráda, "On the Road." In France, Duhamel de Monceau's *Traité de la Culture des Terres* (1753) found a wide readership and was translated into English and published in 1759. His textbook *Élements d'agriculture (1762)* was also widely translated and reprinted. The French repaid the honor in 1801/02 by publishing an 18-volume translation of Arthur Young's works on agriculture and politics under the title *Le Cultivateur Anglais*.

the chemist James Keir.[83] It contained over 500 articles on practical chemistry, arranged alphabetically. Keir supplemented his translation with the most recent discoveries made by Dr. Black, Mr. Cavendish, and others. It was the finest and most accessible compilation of pre-Lavoisier chemical knowledge, and indicative of the great value placed on access to knowledge believed to be potentially useful. There were other such volumes. Richard Watson, elected Professor of Chemistry at Cambridge in 1764 wrote a popular text, *Chemical Essays,* which sold thousands of copies and went through 11 editions. Elementary mathematical knowledge, especially arithmetic and geometry, had to be made accessible cheaply and reliably to a host of craftsmen and skilled artisans, from instrument makers to surveyors to accountants. Here the classic book was Francis Walkingame's *Tutor's Assistant*, which, between its first publication in 1751 and the death of its author in 1783, went through 18 editions, each consisting of between five and ten thousand copies.[84] Formal knowledge was also made more accessible by logical systematization and organization, as illustrated by the detailed indexes that became standard on works of useful knowledge. Taxonomical science was epitomized by the work of Carl Linnaeus, whose classificatory schemes were arguably the most influential scientific endeavor between Newton and Lavoisier, his binomial nomenclature reducing communication and access costs to natural history and botanical knowledge.

Furthermore, access costs had a strictly social dimension. Technological communication inevitably often took the form of personal contact, and such exchanges on knowledge were more effective when the two sides trusted one another. Historically, one of the great sources of technological stagnation had been the social divide between those who knew things ("*savants"*) and those who made things ("*fabricants"*). The relationship between those who possessed useful knowledge and those who might find a use for it was changing in eighteenth-century Europe and points to a further reduction in access costs. To construct pipelines through which those two groups could communicate was at the very heart of the movement.[85] These pipelines, or *passerelles* as Hilaire-Pérez has called them, ran both

[83] Macquer, *Dictionary of Chemistry*. Originally printed in 1771, a fifth edition had already been published by 1777, indicating the success of the work.

[84] Walkingame, *Tutor's Assistant.* By the end of the century, student guidebooks to the *Tutor's Assistant* had appeared. See Wallis, "Early Best-seller," pp. 199–208. Walkingame included mathematical methods employed by glaziers, painters, plasterers, and bricklayers, pointing to the applied and pragmatic nature of the mathematics he taught.

[85] This point was first made by Edward Zilsel in 1942, who placed the beginning of this movement in the middle of the sixteenth century. Although this may be too early for the movement to have much economic effect, the insight that technological progress occurs when intellectuals communicate with producers is central to its historical explanation. Compare Zilsel, "Sociological Roots of Science," pp. 544–60. For a recent restatement, see Jacob, *Scientific Culture*.

ways; they served as a mechanism through which practical people with specific technical problems to solve could air their needs and absorb what best-practice knowledge had to offer—which, of course, at most times was rather little. At the same time, knowledge of crafts and manufactures could influence the research agenda of the scientists, as the Royal Society, at least in its first decades, stressed, by posing focused and well-defined problems. The movement of knowledge was thus bi-directional, as seems natural to us in the twenty-first century. In eighteenth-century Europe, however, such exchanges were still quite novel and it only slowly dawned on people that it would benefit and direct science as much as it would influence industry.[86] By the 1760s in much of Europe the social gap between natural philosophers and entrepreneurs had begun to close, though only very slowly, far too slowly for those who recognized its importance.[87] Social contacts between *savants* and *fabricants* were sufficiently close for Joseph Priestley to marry the sister of the great ironmonger John Wilkinson, and the doyen of British science and president of the Royal Society, Joseph Banks, corresponded with many of the leading industrialists of the time.

Open science and the sharing of useful knowledge meant, of course, that the persons who created this knowledge could not extract the rents it created. Those who added to propositional knowledge would be rewarded by honor, peer recognition, and fame—not a monetary reward proportional to their contribution. For most of the truly great scientists of the era, from Newton to Linnaeus to Lavoisier, the honor and recognition were usually enough if a certain reservation comfort constraint was satisfied. Even those scientists who discovered matters of significant import to industry, such as Claude Berthollet, Joseph Priestley, Benjamin Franklin, and Humphry Davy, often wanted credit, not profit.

[86] Thomas Sprat recognized this in the 1660s when he wrote that no New Atlantis (Bacon's ideal scientific community) was possible unless "Mechanick Labourers shall have Philosophical heads; or the Philosophers shall have Mechanical hands." See Sprat, *History,* p. 397. In its early days, the Royal Society invested heavily in the study of crafts and technology and commissioned a History of Trades, but this effort in the end failed. Compare Hunter, *Establishing the New Science*.

[87] Humphry Davy felt 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, *Discourse*, vol. 2, p. 321. Not all agreed at the time: William Thompson, Count Rumford, noted 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." He expressed hope that the Royal Institution he helped found in 1799 would "facilitate and consolidate" the union between science and art and to direct "their united efforts to the improvement of agriculture, manufactures, and commerce, and to the increase of domestic comfort." See Thompson, *Complete Works*, pp. 743–45.

ACCESS COSTS: INSTITUTIONAL FACTORS

The Industrial Enlightenment consisted in large part of the emergence of institutions devoted to the flow of ideas. Among those, it would seem, Universities should have played a major role. This was surely true for Scotland, where such leading lights as Colin McLaurin, William Cullen, Joseph Black, John Robison, and many others taught courses of considerable technical significance. At the University of Glasgow, many of these courses were opened to artisans and other townspeople interested in studying chemistry and other applied fields. The course taught by Joseph Black in Edinburgh was attended by 200 listeners, and his successor, Thomas Charles Hope, occasionally addressed over 500 auditors.[88] In Germany, a wave of new universities, included that in Göttingen, were founded in the 1740s, training future bureaucrats in agricultural science, engineering, mining, and forestry.[89]

Yet, oddly enough, the role of formal educational institutions in the reduction of access costs was quite modest in the first century of the Industrial Revolution.[90] English universities were rather ineffective in teaching applied science and mechanics in this period, although the gap was made up in part by the Scottish universities, and in part by 60 or so dissenting academies, which taught experimental science, mathematics, and botany among other subjects. Among those, Warrington Academy was one of the best, and the great chemist Joseph Priestley taught there for a while, though surprisingly he was made to teach history, grammar, and rhetoric.[91] Although these institutions reached only a thin elite, apparently that was enough. In the early nineteenth century, there were some attempts to close the educational gap between classes by means of the so-called Mechanics Institutes, inspired by George Birckbeck, which supplied adult education

[88] Wood, "Science," p. 109.

[89] Outram, *Enlightenment*, p. 60.

[90] Oxford and Cambridge have been given little credit for teaching much of value to a vibrant economy, and their enrollments declined in the eighteenth century. Adam Smith in a famous sentence remarked sarcastically that at Oxford the dons had "long ago given up all pretence of teaching," and Priestley compared them to "pools of stagnant water." There were a few exceptions, especially in Cambridge where Richard Watson was "chiefly concerned with manufacturing processes rather than with the advancement of pure science" and John Hadley who showed a "noticeable interest in industrial-chemical processes" (Musson and Robinson, *Science and Technology*, pp. 168, 36). His colleague in Magdalene College, John Rowning, was a mathematician who wrote a popular *Compendious System of Natural Philosophy* that went through seven editions between 1735 and 1772. Birse has collected data that show that out of 498 applied scientists and engineers born between 1700 and 1850, 91 were educated in Scotland, 50 at Oxbridge, and 329 (about two-thirds) had no university education at all. See Birse, *Engineering*, p. 16. Over the eighteenth century, moreover, the number of engineers and applied scientists who received a formal institutionalized education declined.

[91] Schofield, *Lunar Society*, p. 195.

in the evening, with the purpose of bridging the gap between the working class and science.[92] Contemporaries noted that these institutes by and large failed in their objective to spread scientific knowledge to the masses and mostly provided remedial education to laborers, as well as scientific knowledge to members of the skilled labor aristocracy.[93]

The other institutional mechanism emerging during the Industrial Enlightenment to connect those who possessed prescriptive knowledge to those who wanted to apply it was the emergence of meeting places where men of industry interacted with natural philosophers. Many of these meetings were ad hoc lectures and demonstrations by professional lecturers and popularizers.[94] A. E. Musson and Eric Robinson, who were among the first to recognize the significance of these lecturers point out that only a few of them were of national significance, whereas others were "mostly local" figures.[95] Much of the improved access to useful knowledge took place through informal meetings of which we have but poor records, in coffee houses and pubs, improvised lectures, and private salons.[96] By 1700 there were 2,000 coffeehouses in London, many of which were sites of learning, literary activity, and political discussions. Perhaps the most famous of

[92] Inkster, "Social Context," pp. 277–307.

[93] Roderick and Stephens, *Education*, pp. 54–60.

[94] Of the itinerant lecturers, the most famous was John T. Desaguliers. Desaguliers, a leading proponent of Newton with an international reputation (he lectured in the Netherlands) received a royal pension of £70 per annum as well as a variety of patents, fees, and prizes. His *Course of Mechanical and Experimental Philosophy* (1724) was based on his hugely popular lectures on science and technology. William Whiston, one of Newton's most distinguished proponents and successor at Cambridge "entertained his provincial listeners with combinations of scientific subjects and Providence and the Millennium." James Jurin, master of the Newcastle Grammar School, gave courses catering to the local gentlemen concerned with collieries and lead-mines. (See Stewart, *Rise,* p. 147). Other British lecturers of note were Peter Shaw, a chemist and physician, the instrument maker Benjamin Martin, Stephen Demainbray who lectured both in France and England and later became Superintendent of the King's Observatory at Kew, and the Reverend Richard Watson at Cambridge whose lectures on Chemistry in the 1760s were so successful that he drew a patronage of £100 for his impoverished chair. In France the premier lecturer and scientific celebrity of his time was Abbé Jean-Antoine Nollet, whose fame rests on early public experiments with electricity (he once passed an electrical charge from a Leyden jar through a row of Carthusian monks more than a mile long). Nollet also trained and encouraged a number of his disciples as lecturers, as well as some of the most celebrated scientists of his age, such as Lavoisier and Monge. Similarly, Guillaume-François Rouelle's lectures on chemistry in the Jardin du roi drew an audience that included Rousseau, Diderot, and even Lavoisier himself. Compare Stewart, "Laboratory." In Napoleonic France, the "best scientific minds of the day" were lecturing to the public about steam engines, and it became common to regard some scientific training as a natural prelude for entrepreneurial activity (Jacob, "Putting Science").

[95] For a magisterial survey, see Musson and Robinson, *Science*, pp. 87–189.

[96] In the closing years of the seventeenth century, the Marine Coffee House in Birchin Lane behind the Royal Exchange in London was the first location for an organized set of lectures on mathematics given by the Reverend John Harris, to be followed by a series on experimental philosophy. See Stewart, "Selling of Newton," p. 180. Among the best-known private eighteenth-century Paris *salons* were those of Mme de Tencin and Mme l'Espinasse.

these coffee house societies was the London Chapter Coffee House, the favorite of the fellows of the Royal Society, whose membership resembled (and overlapped with) the Birmingham Lunar Society.[97] Masonic lodges, too, proved a locus for the exchange of scientific and technological information even if that was not their primary mission.[98] Lecturers performed entertaining public experiments, in which electricity and magnetism played roles disproportionate to their technical significance. Needless to say, there are other explanations for the popularity of scientific lectures, not all of them persuasive.[99]

After 1750 informal meetings started to slowly dwindle in importance, as they were replaced by more formal organizations, but the demand for useful knowledge remained strong. The establishment of the Royal Society in 1662 was one of the first signs of what was to come. There had, of course, been precedents, such as the *Accademia dei Lincei* founded in 1603 in Rome and disbanded in 1630. Formal academies were founded and bankrolled by states or local governments, whereas spontaneous societies, often specialized, were organized by their participants. It is striking to what degree this phenomenon in the eighteenth century became a *provincial* phenomenon; small towns increasingly found they had the critical mass of interested persons to form a formal club devoted to scientific and technological discourse. Of those, a few have attained fame as the kind of organizations that were instrumental in bringing about the Industrial Revolution, none more so than the Birmingham Lunar Society.[100] Knowledge exchange was the very raison d'être of the Birmingham Lunar Society, which provided routine contact between scientists such as Priestley and Keir, mechanics such as Whitehurst and Watt, and entrepreneurs such as Boulton and Wedgwood.[101]

[97] Levere and Turner, *Discussing Chemistry*. Its membership reads like a veritable list of the "Who's who" of the British Industrial Enlightenment of the 1780s. Needless to say, many of these lecturers structured their lectures around topics that had no immediate or even remote applicability, presented theories that were bogus even by the standards of the time, and at times they showed a bias toward the flashy and dramatic experiment over the strictly useful. Schaffer, "Natural Philosophy," pp. 1–43. Desaguliers himself admitted that "a great many persons get a considerable knowledge of Natural Philosophy by way of amusement" (cited by Schaffer, "Machine Philosophy," p. 159). But as Stewart ("Laboratory," p. 8) remarks, "a sense of practical consequence was not immediately excluded by the spectacular."

[98] On the significance of Masonic Lodges, see Jacob, *Living the Enlightenment*; and Im Hoff, *Enlightenment*, pp. 139–45.

[99] Elliott, "Birth," p. 96, apparently influenced by notions of the "Habermasean public sphere," thinks that their attractiveness came from their being intellectually challenging, morally uplifting, and that they enhanced polite education while not being socially disruptive and offering no threat to peace and stability. This would equally apply to lectures on classical sculpture or cooking classes.

[100] This is most eloquently expressed by Uglow, *Lunar Men*. See also the classic Schofield, *Lunar Society*.

[101] In 1776 Josiah Wedgwood consulted his fellow Lunar Society member, the chemist James Keir, on matters of heating vitreous substances, and together they discovered a way to reduce the

In France, great institutions were created under royal patronage, above all the *Académie Royale des Sciences*, created by Colbert and Louis XIV in 1666 to disseminate information and resources.[102] Yet the phenomenon was nationwide: McClellan estimates that 33 official learned societies were functioning in the French provinces during the eighteenth century, counting over 6,400 members, and that overall during the eighteenth century perhaps between 10,000 and 12,000 men belonged to learned societies that dealt at least in part with science.[103] The *Académie Royale* exercised a fair amount of control over the direction of French scientific development and acted as technical advisor to the monarchy. By determining what was published and exercising control over patents, the *Académie* became a powerful administrative body, providing scientific and technical advice to government bureaus.[104] French academies had a somewhat different objective than did British: it is often argued that the *Académie* linked the aspirations of the scientific community to the utilitarian concerns of the government, creating not a Baconian society open to all comers and all disciplines but a closed academy limited primarily to Parisian scholars. French science was in some ways different from British science, both in its agenda and its methodology. Yet the difference between France and Britain was one of emphasis and nuance, not of essence: they shared a utilitarian optimism of man's ability to create wealth through knowledge. French science, as the old truism has it, was more formal, deductive, and abstract than British science, which had a pragmatic and more experimental bend.[105] But instead of a source of weakness, this diversity ultimately provided the Enlightenment project with strength through, as it were, a division of labor between various societies specializing in the areas of their comparative advantage. Rather than a set of competing players or a horse race, we should regard the European Enlightenment as a joint project in which collective knowledge was produced, increasingly accessible to the participants.

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veins and streaks that disfigured glass at the time. See Schofield, *Lunar Society*, p. 172. Henry Cort, whose invention of the puddling and rolling process was no less central than Watt's separate condenser, also consulted Joseph Black during his work. Compare Clow and Clow, *Chemical Revolution*.

[102] Its membership included most of the distinguished scientists of France in the eighteenth century including d'Alembert, Buffon, Clairaut, Condorcet, Fontenelle, Laplace, Lavoisier, and Reaumur. It published the most prestigious and substantive scientific series of the century in its annual proceedings *Histoire et Memoires* and sponsored scientific prize contests such as the Meslay prizes. It recognized achievement and rewarded success for individual discoveries and tried to enhance the social status of scientists by granting salaries and pensions. A broad range of scientific disciplines were covered, with mathematics and astronomy well represented, and botany and medicine not less prominent.

[103] McClellan, "Academie Royale des Sciences," p. 547.

[104] Hilaire-Pérez, *L'invention technique,* pp. 37, 50. Gillespie, *Science . . . End of Old Regime*, pp. 81–99, 461–63.

[105] For a recent statement, see Jacob and Stewart, *Practical Matter*, p. 119.

Elsewhere on the Continent, too, there was a growing recognition of the importance of the creation of new useful knowledge and improved access to the entire stock. In the Netherlands, rich but increasingly technologically backward, heroic efforts were made to infuse the economy with more innovativeness.[106] In Germany, provincial academies to promote industrial, agricultural, and political progress through science were founded in all the significant German states in the eighteenth century. The Berlin Academy was founded in 1700 and in its early years directed by the great Leibniz. Among its achievements was the discovery that sugar could be extracted from beets (1747). Around 200 such societies appeared in Germany during the half century spanning from the Seven Years War to the Napoleonic occupation of Germany, such as the Patriotic Society founded at Hamburg in 1765.[107] Many of the German societies were dedicated to political economy, emphasizing what they believed to be the welfare of the population at large and the country over private profit. Local and provincial societies supplemented and expanded the work of national academies.[108] Publishing played an important role in the work of societies bent on the encouragement of invention, innovation, and improvement, reflecting the growing conviction that through the diffusion of useful knowledge somehow the public good was enhanced. At the level of access to propositional knowledge, at least, there is little evidence that the *ancien régime* was incapable of generating sustained progress.

[106] The first of these was established in Haarlem in 1752, and within a few decades the phenomenon spread (much as in England) to the provincial towns. The Scientific Society of Rotterdam known oddly as the *Batavic Association for Experimental Philosophy* was the most applied of all, and advocated the use of steam engines (which were purchased in the 1770s but without success). The Amsterdam Society, known as *Felix Meritis*, carried out experiments in physics and chemistry. These societies stimulated interest in physical and experimental sciences in the Netherlands, and they organized prize-essay contests on useful applications of natural philosophy. A physicist named Benjamin Bosma for decades gave lectures on mathematics, geography, and applied physics in Amsterdam. A Dutch Society of Chemistry founded in the early 1790s helped to convert the Dutch to the new chemistry proposed by Lavoisier (see Snelders, "Professors"). The Dutch high schools, known as *Athenea,* taught mathematics, physics, astronomy, and at times counted distinguished scientists among their staff.

[107] Lowood, *Patriotism*, pp. 26–27.

[108] Lowood, *Patriotism*, has argued that the German local societies were predominantly private institutions, unlike state-controlled academies, which enabled them to be more open, with few conditions of entry, unlike the selective, elitist academies. They broke down social barriers, for the established structures of Old Regime society might impede useful work requiring a mixed contribution from the membership of practical experience, scientific knowledge, and political power. Unlike the more scientifically inclined academies, they were open to a wide circle of occupations, including farmers, peasants, artisans, craftsmen, foresters, and gardeners, and attempted to improve the productivity of these activities. Prizes rewarded tangible accomplishments, primarily in the agricultural or technical spheres. Unlike earlier academies, their goal was not to advance learning, but rather to apply useful results of human knowledge, discovery, and invention to practical and civic life.

Some of these societies fit perfectly into the idea of an Industrial Enlightenment. One such was the Society of Arts, founded in 1754, which made a point of encouraging invention by awarding prizes, publicizing new ideas, and facilitating communication between those who possessed useful knowledge and those who could use it. 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."[109] In Britain, most of these societies were the result of private initiatives and funds, whereas on the Continent they were usually supported by local or national government. Yet these were differences of degree, not of essence, and certainly not of ideology.[110]

What did these scientific societies do to further economic development in Europe? They organized lectures, symposia, public experiments, and discussion groups, and published "proceedings" on a variety of topics. Many of them had prize essay contests. Much of the material discussed by these organizations was of course quite remote from economic applications. Many of them were meant to standardize languages, or were engaged in discussing issues of archaeology and local history. Others discussed music, the arts, poetry, and the theater. A substantial number of them were either the drinking clubs of a bored leisure class or the pet projects of local nobles, magistrates, or bourgeois busybodies to show off to the next town or county.[111] But in the course of the eighteenth century "natural history" and "experimental philosophy" increasingly started to play a role in these learned societies. Agriculture, chemistry, botany, mineralogy, geology, and medicine became topics around which entire organizations pivoted.[112] They were without any question an elite phenomenon,

[109] 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.

[110] Allan, "Society," pp. 434–52.

[111] For a good summary see McClellan, "Learned Societies," pp. 371–77. See also the six entries under "academies" in id., vol. 1, pp. 4–17.

[112] The first agricultural "improvement society" in Britain was the *Scottish Honorable Society of Improvers of the Knowledge of Agriculture* (founded in 1723 and disbanded in 1745 after the rebellion). Ireland followed suit in 1731 with the Dublin Society established "to promote the development of agriculture, arts, science and industry in Ireland." The 1750s and 1760s witnessed the founding of such agricultural societies as the Scottish *Gordon's Mill Farming Club,* founded in 1758, by Thomas Gordon of Aberdeen University on the idea that "agriculture ought to be considered as a noble & important branch of natural Philosophy." The Continent was not far behind. The

and as such their direct impact was limited. However, as Jürgen Habermas has maintained, at least the theory—if not the practice—of formal and informal meeting places in the eighteenth century was for members to disregard status and wealth and treat one another as equals, recognizing only the authority of a "better argument."[113] To be sure, the bulk of their work—as in all creative processes—was wasteful, wrong-headed, and ineffective.[114] But the membership shared a desire to make useful knowledge more accessible, an important trend in the intellectual development of Europe that helped to create the foundation of sustained technological progress in the nineteenth century through reduced access costs.

ACCESS COSTS: ECONOMIC FACTORS

The economic issue of the endogeneity of access costs must be confronted head-on. The decline in access costs was not, of course, a purely supply-driven process. The demand for such technical knowledge by the inventors of the time is exemplified by the rise in technical publications and technical essays in general-purpose periodicals that popularized and summarized best-practice research, and did not publish original findings but popularized and summarized (and often plagiarized) best-practice research published elsewhere. The influence of the Industrial Enlightenment came from both sides, the desire of the *savants* to give and the desire of the *fabricants* to receive. The only attempt to date to try to estimate the impact of exogenous variables such as population and relative prices on the diffusion of knowledge in agriculture is an important and neglected paper by L. Simon and Richard Sullivan.[115] Thinking of it in a supply and demand framework may, however, not be the only way to think of the mechanisms

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idea of agricultural progress on the eighteenth-century Continent was personified in the work of Duhamel du Monceau, a French *agronome* and "specialist in things English" and in that of the German Albrecht Thaer. The Florence *Accademia dei Georgofili* (1753) and the *Société d'Agriculture, de Commerce et des Arts de Bretagne* (1757) in Rennes were followed by the *Académie d'Agriculture de la France* (1761), the Royal Danish agricultural society (1769) and many others. Terms such as "useful knowledge" start cropping up increasingly after 1750, in the names and charters of institutions such as the *Akademie Gemeinnütziger Wissenschaften zu Erfurt* and the British *Society for the Encouragement of Arts, Manufactures and Commerce* (both founded in 1754).

[113] Habermas, *Structural Transformation*, p. 36.

[114] This was well expressed by Eric Jones 20 years ago: "Much of the activity of the science subculture, the club meetings, the flooding exchange of information by mail, fell by the wayside as far as material gain was concerned at the hands of tired or dilettantish or unlucky individuals . . . Nevertheless there was so very much activity . . . that some seeds from hobby science and technological curiosity were almost certain not to fall on stony ground." Jones, "Subculture," p. 877.

[115] Simon and Sullivan, "Population Size," pp. 21–44. They find the growth of publications and patenting to depend on population size and the relative price of food products. The problem of course is that if the relative price of agricultural goods explains publication of tracts on farming technology, how can we explain the increase of works in chemistry, mechanics, and mathematics?

leading to the Industrial Enlightenment. An alternative view would regard it as an evolutionary process, in which elements of an entity called "useful knowledge" multiplied and were "selected for" in a environment conducive to growth and diffusion of knowledge that eventually became economically productive.

In any event, in the closing decades of the seventeenth century and the first half of the eighteenth, a market for "commodified" useful knowledge started to emerge and became a hallmark of the Industrial Enlightenment. Professional scientists such as John Harris, James Hodgson, William Whiston, and John T. Desaguliers made money by lecturing, consulting, and publishing.[116] Larry Stewart has referred to these men as "entrepreneurs of science" who found that they had a commodity to sell that people with money found attractive.[117] During the Industrial Revolution, these markets for consultants expanded and became more formal.[118] Intellectual property rights in useful knowledge tend on the whole to enhance such markets, because by taking out a patent, the inventor placed the invention in the public realm and had an incentive to publicize it rather than keep it secret.

Some Enlightenment figures made a career (and often a good living) out of specializing in building such bridges between propositional and prescriptive knowledge, and might therefore be called access-cost reducers or facilitators. Among them was William Shipley, famous for founding the Society of Arts, but also the Maidstone Society, which was expanded later into the Kentish Society for Promoting Useful Arts. Not a very creative or original individual himself, he was highly active in the management of the Society of Arts and in agricultural improvements in Kent where he had a country home, a hotbed of farm innovation. His credo is summed up in his "plan" for the establishment of the Society of Arts: "Whereas the Riches, Honour, Strength and Prosperity of a Nation depend in a great Measure on Knowledge and Improvement of useful Arts, Manufactures, Etc. . . . sev-

[116] For details on their careers, see Jacob and Stewart, *Practical Matter*, pp. 61–92

[117] Stewart, "Selling," p. 181.

[118] Such markets often concerned technical consultants such as the great John Smeaton and the "Smeatonian" engineers that followed his example. Soho-trained engineers traveled widely through Britain, dispensing expertise. The clock- and instrument maker John Whitehurst, a charter member of the Lunar Society, consulted for every major industrial undertaking in Derbyshire, where his skills in pneumatics, mechanics, and hydraulics were in great demand; Joseph Priestley worked as a paid consultant for his fellow "lunatics" Wedgwood and Boulton. See Elliott, "Birth," p. 83. Schofield, *Lunar Society*, pp. 22, 201. Another striking example is the emergence of so-called coal viewers who advised coal mine owners on the optimal location and structure of coal mines, the use of equipment, and similar specific issues. Sidney Pollard recounts that these consultants were often called to check on one another, which clearly enhanced their credibility, and that they were generally the "fountain-head" of managerial and engineering talent in the engineering industry. Pollard, *Genesis*, p. 153.

eral [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."[119] A second was John Coakley Lettsom, famous for being one of London's most successful and prosperous physicians and for liberating his family's slaves in the Caribbean. He corresponded with many other Enlightenment figures including Benjamin Franklin, Erasmus Darwin, and the noted Swiss physiologist Albrecht von Haller. He wrote a book about the natural history of tea and was a tireless advocate of the introduction of mangel-wurzel into British agriculture.[120] Another was William Nicholson, the founder and editor of the first truly scientific journal, namely *Journal of Natural Philosophy, Chemistry, and the Arts* (more generally known at the time as *Nicholson's Journal*), which commenced publication in 1797.[121] It published the works of most of the leading scientists of the time, and functioned much as do today's *Nature* or *Science*, that is, to announce important discoveries in short communications.[122] Or consider Richard Kirwan, the living spirit behind the London Chapter Coffee House Society in the 1780s. An Irish lawyer, chemist, and mineralogist, trained in France and close to many French scientists, Kirwan brought together scientists, instrument makers, and industrialists to discuss how science could be applied. Like other facilitators, he was an ardent letter writer, who corresponded with all the leading *savants* of Europe, even the Russian Empress Catherine. He wrote the first systematic treatise on Mineralogy (1784), which was soon translated into French, German, and Russian. Elected president of the Royal Irish Academy from 1799 to 1812, he contributed to the introduction of chlorine bleaching into Ireland. Kirwan, too, despite being one of the most respected chemists of his age, was no pioneering scientist and fought a doomed rear-guard action against the anti-phlogiston chemistry imported from France.[123] A fifth Briton who fits this description

[119] Allan, *William Shipley,* p. 192.

[120] Lettsom, *Natural History.* Lettsom was only one of many who translated experimental and empirical data about tea into positive medical recommendations. See MacFarlane, *Savage Wars*, pp. 146–47.

[121] Nicholson was also a patent agent, representing other inventors. Around 1800 he ran a "scientific establishment for pupils" on London's Soho square. The school's advertisement announced that "this institution affords a degree of practical knowledge of the sciences which is seldom acquired in the early part of life," and promised to deliver weekly lectures on natural philosophy and chemistry "illustrated by frequent exhibition and explanations of the tools, processes and operations of the useful arts and common operations of society."

[122] In it, leading scientists including John Dalton, Berzelius, Davy, Rumford, and George Cayley communicated their findings and opinions. Yet it also contained essays on highly practical matters, such as an "Easy Way of churning Butter" or a "Description of a new Lamp upon M. Argand's Principle."

[123] His "Essay on Phlogiston" was translated by none other than Mme. Lavoisier herself, with adverse commentaries appended by her husband, as well as Berthollet, Monge, and Morveau. In 1791

as a mediator between the world of propositional knowledge and that of technology was Joseph Banks, one of the most distinguished and respected botanists of his time whose life was more or less coincident with the Industrial Revolution. Wealthy and politically well connected, Banks was a co-founder (with Rumford) of the Royal Institution in 1799, a friend and scientific consultant to George III, and president of the Royal Society for 42 years. Banks labored tirelessly to help bring about the social and economic improvement the Baconian program advocated, corresponded with many people, supported every innovative branch of manufacturing and agriculture, and was the dominant political figure in Britain's world of science for much of his life. Among his close friends were the agricultural improvers John Sinclair and Arthur Young, as well as two pillars of the Industrial Revolution, Matthew Boulton and Josiah Wedgwood. He was associated with, among others, the Society for the Arts, before taking over the Royal Society, which he ruled with an iron if benign hand.[124] He was every inch an enlightenment figure, devoting his time and wealth to advancing learning and to using that learning to create wealth, "an awfully English *philosophe"* in Roy Porter's memorable phrase.[125]

Britain had no monopoly on such facilitators, The same traditions can be observed on the Continent, although after 1789 some talented persons were distracted by and diverted into political or military careers. Among the more notable of them was Henri-Louis Duhamel de Monceau, a noted *agronome* and the chief editor of the massive *Descriptions des Arts et Métiers*.[126] François Rozier (1734–1793), another *agronome* and scientific entrepreneur, "a clergyman whose vocation was the enlightenment" in Gillispie's succinct characterization, publisher of the *Observations sur la Physique, sur l'Histoire Naturelle, et sure les Arts,* widely regarded as the first independent periodical to be concerned wholly with advances in cutting-edge science.[127] Jean-Antoine Chaptal, a noted chemist, successful entrepreneur, and Minister of the Interior early in the rule of Bonaparte, played a major part in the founding of the *Societé d'Encouragement pour l'Industrie Nationale* and "sought to instill a new scientific ideology to educate entrepreneurs in applied science and engineers in business

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Kirwan admitted his conversion to the antiphlogistonist position. Lever and Turner, *Discussing Chemistry,* passim. See also Reilly and O'Flynn, "Richard Kirwan," pp. 298–319.

[124] Drayton, *Nature's Government*, chap. 4. Gascoigne, *Joseph Banks*, passim.

[125] Porter, *Creation*, p. 149.

[126] For details see Bourde, *Agronomie*, pp. 253–76, 313–68. Gillispie, who also studied Duhamel in some detail summarized his intellectual persona: "his hallmark was neither style nor wit but usefulness." Condorcet, in his eulogy, wrote of him that in his writings he expected little prior knowledge of his readers and composed his works, not for scientists but for persons who would put what they had learned to use. See Gillispie, *Science . . . End of Old Regime*, p. 338.

[127] McClellan, "Scientific Journals," pp. 45–46. Gillispie, *Science . . . End of Old Regime*, p. 188.

savvy."[128] His *Chimie appliqée aux arts,* published in four volumes in 1807, became the standard work in industrial chemistry in the early decades of the nineteenth century. Another was Alexandre Vandermonde, a mathematician who was deeply attracted to machinery and technology and collaborated with the famed French inventor Jacques Vaucanson. His most famous contribution was to be the "principal organizer" behind the research project that resulted in the first major industrial application of Lavoisier's new chemistry, namely the *"mémoire sur le fer"* (published jointly with the more famous Gaspard Monge and Claude Berthollet in 1786).[129] Less well known was Henri de Goyon de la Plomanie, who in 1762 published a two-volume work, *La France Agricole et Marchande*, popularizing a number of inventions in the field of farm implements and hydraulics.[130] In Germany, an early figure in this tradition was Johann Joachim Becher (1635–1682), an alchemist, engineer, mathematician, physician, and courtier.[131] On the Continent, courts played a far more central role in this process than in Britain, where this intellectual arbitrage was largely carried out by the private sector.

As might be expected, in some cases the bridge between propositional and prescriptive knowledge occurred within the same mind: the very same people who also were contributing to science made some critical inventions (even if the exact connection between their science and their ingenuity is not always clear).[132] In doing so, they not only facilitated the bidirectional flows of knowledge, but also created hybrid practices in which the standards and methods of one sphere were applied to another. The spheres were always overlapping, but during the nineteenth century some specialization did set in.[133] Among the inventions made by people whose main fame rests on their scientific accomplishments were the chlorine

[128] Jacob, "Putting Science to Work." An excellent survey of Chaptal's career and importance is contained in Horn and Jacob, "Jean-Antoine Chaptal," pp. 671–98. See also Gillispie, *Science . . . Napoleonic Years,* pp. 611–34.

[129] The paper established beyond any doubt the chemical differences between cast iron, steel, and wrought iron, and attributed the differences in physical properties to differences in carbon content without the use of phlogiston. See Gillispie, *Science . . . End of Old Regime*, pp. 438–44.

[130] de la Plombanie, *La France Agricole*, pp. 342–462. In Bourde's assessment, he combined beauty with truth in his description and depiction of these tools.

[131] Smith, *Business*, characterizes his career as "halfway between the world of artisans and that of scholars, he became an intermediary—both physical and intellectual—between them" (p. 5, see also pp. 71–77).

[132] Kranakis, "Hybrid Careers," pp. 177–204. One of her examples is the French engineer and mathematician Claude-Louis Navier (1785–1836), who, among others, used the recently developed Fourier analysis to analyze the vibration in suspension bridges, and did pioneering work in fluid dynamics for which he is still famous. His work, and that of other *polytechniciens*, was highly abstract and mathematical, and of long-term rather than immediate applicability.

[133] As I have argued elsewhere, the adoption of the scientific *method* by inventors and engineers in the eighteenth century was central to the acceleration of technological progress. See Mokyr, *Gifts*, pp. 36–38.

bleaching process, first suggested by Lavoisier's most illustrious student, Claude Berthollet, the invention of carbonated (sparkling) water and rubber erasers by Joseph Priestley, and the "miners friend," the safety lamp to be used in collieries invented by the leading scientist of his age, Humphry Davy (who also wrote a textbook on agricultural chemistry and discovered that a tropical plant named catechu was a useful additive to tanning). As noted already, many of those "dual" career minds seemed uninterested in making money from their inventions, presumably applying the ethics of open science to the diffusion of technology.[134] Incentives were, as always, central to the actions of the figures of the Industrial Enlightenment, but rather we should not assume that these incentives were the same for all. Nor were they necessarily the same in the age of Enlightenment and in the modern age. In our own post-Schumpeterian world, in which most R&D is carried out by corporate entities, the financial bottom line may well be the dominant motive; in an earlier day, when the decisions were made largely by independent individuals, ambition, curiosity, and altruism may have had a larger role relative to naked greed.

THE INDUSTRIAL ENLIGHTENMENT AND ECONOMIC GROWTH

The Industrial Enlightenment, thus, had two dimensions. One was to expand the body of propositional knowledge and to steer it in those directions that might turn out to be useful, that is, both to increase research and to adjust its agenda to make it more likely for discoveries to have useful applications. The second was a deliberate effort to reduce access costs to *existing* knowledge. As noted, those two objectives were not independent, but rather neatly complemented one another. Although they were, of course, like the rest of the Enlightenment, confined to a small elite in the West and never constituted a mass movement, that elite was pivotal in igniting the processes that brought about the Industrial Revolution. Natural philosophers, physicians, engineers, skilled mechanics, and entrepreneurs combined to change the rate and direction in which new useful knowledge was accumulated and diffused.

How much did all this matter? To dwell on one example of the effect of the improved access to knowledge, consider the development of steam power. There is little doubt that the scientific milieu of Glasgow in which Watt lived was indispensable to his technical abilities. He maintained di-

[134] Richard Kirwan was "philosophically indifferent to money," and William Nicholson was "continually occupied in useful work but failed to derive any material advantages from his labour." (Dictionary of National Biography, vol. 11, p. 229; vol. 14, p. 475. Not all scientists eschewed such profits: the brilliant Scottish aristocrat Archibald Cochrane (Earl of Dundonald) made a huge effort to render the coal tar process he patented profitable, but failed and ended up losing his fortune.

rect contact with the Scottish scientists Joseph Black and John Robison, and as H. W. Dickinson and Rhys Jenkins note in their memorial volume, "one can only say that Black gave, Robison gave, and Watt received."[135] Whether or not Watt's crucial insight of the separate condenser was due to Black's theory of latent heat, there can be little doubt that the give-and-take between the scientific community in Glasgow and the creativity of men such as Watt was essential in smoothing the path of technological progress.[136] Much the same can be observed in Cornwall a bit later.[137] Decades later, the work of Mancunians Joule and Rankine on thermodynamics led to the development of the two cylinder compound marine steam engine.[138] The growth of a machine culture in the eighteenth century involved a close collaboration and interaction between natural philosophy and highly skilled craftsmen, grappling with difficult mechanical issues such as heat, power, inertia, and friction, recently described by Larry Stewart.[139] The same is true in many other key industries, especially chemical and engineering, and although it is not nearly as obvious in textiles, access to developments in one industry inspired and stimulated inventors elsewhere.[140]

Nothing of the sort, I submit, can be detected at this time in the Ottoman Empire, Japan, India, Africa, or China. Floris Cohen, indeed, has argued flat-out that Francis Bacon was a typically European figure, who could not possibly have come from anywhere else.[141] The Enlightenment touched lightly (and with a substantial delay) upon Iberia, Russia, and South Amer-

[135] Dickinson and Jenkins, *James Watt*, p. 16.

[136] Hills explains that Black's theory of latent heat helped Watt compute the optimal amount of water to be injected without cooling the cylinder too much. More interesting, however, was his reliance on William Cullen's finding that in a vacuum, water would boil at much lower, even tepid temperatures, releasing steam that would ruin the vacuum in a cylinder. In some sense that piece of propositional knowledge was essential to his realization that he needed a separate condenser. Hills, *Power*, p. 53.

[137] Richard Trevithick, the Cornish inventor of the high pressure engine, posed sharp questions to his scientist acquaintance Davies Gilbert (later President of the Royal Society), and received answers that supported and encouraged his work. See Burton, *Richard Trevithick*, pp. 59–60.

[138] Thermodynamics not only made essential contributions to the design of steam engines, such as pointing to the advantages of compounding and steam-jacketing, but also created an entirely new way of thinking about what thermal efficiency was and how to measure it. Most important, the widening of the understanding of power technology in this direction pointed to what could *not* be done, for example the realization that John Ericsson's caloric engine (1853) based on the idea that energy could be "regenerated" (that is, used over and over again) was impossible. See Bryant, "Role."

[139] Stewart, "Meaning."

[140] In Leeds, for instance, both the flax-spinner John Marshall and the woolen manufacturer Benjamin Gott had wide-ranging interests in hydraulics, bleaching, mechanics, and related topics. In Manchester, M'Connell and Kennedy, one of the most successful early cotton manufacturers were highly technologically "literate" and closely involved with the Manchester Philosophical and Literary society.

[141] Cohen, "Causes." In a similar vein, Mark Elvin, "Some Reflections," p. 58, notes whereas Giambattista Dellaporta, who dominated the *Accademia dei Lincei* in its early days, can be compared to a Chinese intellectual of that time, he was replaced by Galileo, who cannot.

ica, but in many of these areas it encountered powerful resistance and retreated. Science, ingenuity, and invention, as many scholars have rightly stressed, had never been a European monopoly, and much of their technological creativity originated with adopting ideas and techniques the Europeans had observed from others. But by discovering the fundamental processes through which knowledge can create more knowledge and creating the institutional environment that facilitated these processes, the Industrial Enlightenment unlocked the path to cumulative growth in the West. The hard question that needs to be answered is not so much why this movement emerged at all, but what explains its triumph in the societies we now associate with "the West." That victory was at times attained through violent revolution imposed by foreign occupiers, but in Britain the success of the Enlightenment, on the whole, met little determined opposition, and as a result has tended to be underrated by historians of the eighteenth century.[142] With the success of the Enlightenment program came rising living standards, power, comfort, and wealth in the societies in which it was victorious. The stationary state was replaced by the steady state. It is Europe's intellectual development rather than its coal or its colonial ghost acreage that answers Pomeranz's query of why Chinese science and technology—which did not "stagnate"—"did not revolutionize the Chinese economy."[143]

The Industrial Enlightenment insisted on asking not just "which techniques work" but also "why techniques work" (that is, what natural regularities explain their success). The search for higher levels of generality and encompassing natural regularities were inherent in the massive intellectual heritage of Isaac Newton. The influence of the Newtonians grew steadily through Western Europe in the first half of the eighteenth century, often overlapping with the Enlightenment. Access costs to Newton's work was high because, as Voltaire said, to read Newton the student must be deeply skilled in mathematics and many Enlightenment thinkers worked hard to make Newton's writings more accessible.[144] Newton's philosophy of Nature went far beyond his mathematics and physics; it was an essentially empirical approach in which facts and phenomena were primary and

[142] As J. H. Plumb has noted, "Too much attention . . . is paid to the intellectual giants, too little to their social acceptance. Ideas acquire dynamism when they become social attitudes, and this was happening in England," compare Plumb, "Reason," p. 24.

[143] Pomeranz, *Great Divergence,* p. 48.

[144] Reprinted in Jacob, *Enlightenment,* p. 104. Voltaire himself did as much as anyone to popularize Newton's work on the Continent, including his *Elémens*. An interesting case in this regard is the career of Voltaire's companion, the Marquise de Châtelet (1706–1749), one of the most remarkable female Enlightenment figures, who published one of the more user-friendly translations of Newton's work into French. In a touching preface, Voltaire dedicated his work to this "*vaste et puisante génie, Minerve de la France, immortelle Emilie, disciple de Neuton & de la Verité*."

any generalizations and principles were constrained by them rather than true *a priori* as the Cartesians held.[145]

The men and women of the Industrial Enlightenment increasingly felt that a research program based on an empirical-experimentalist approach held the key to continuing economic and social progress. Physicists, engineers, chemists, botanists, medical doctors, and agricultural improvers made sincere efforts to generalize from the observations they made, to fit observed facts and regularities (including successful techniques) to the formal propositional knowledge of the time. The bewildering complexity and diversity of the world of techniques in use was to be reduced to a finite set of general principles governing them. The success of such attempts varied enormously with the complexity of the matter at hand.[146]

Posing the questions *why* and *how* a technique worked was of course much easier than answering them. In the longer term, however, raising the questions and developing the tools to get to the answers were essential if technical progress was not to fizzle out.[147] The way to phrase the question was set out by Newton: he never explained *why* gravity existed, but its generality was the explanation of a bewildering host of real-world phenomena. Priestley and Lavoisier followed the same methodology. It is interesting that the late Enlightenment was willing to concede the depth of understanding for greater effectiveness. The Standard Model of physics, formulated by Laplace at the end of half a century of research, was something that gave reasonable and workable approximations rather than had any claims to the "truth." As Heilbron puts it, quantifying chemists and physicists surrendered their claims to "Truth" in exchange for convenience of thought and ease of computation.[148] An instrumentalist approach to propositional knowledge looked for exploitable empirical relations between natural forces and phenomena without wondering too deep and too hard about the metaphysics. As Gillispie has noted, if science was of any help to production, it was descriptive and experimental rather than analytical science. The triumph of that approach was in the revolution that Antoine Lavoisier brought about in chemistry. His *Élements*, complemented by

[145] Cassirer, *Philosophy*, pp. 51–56.

[146] Thus Erasmus Darwin, grandfather of the biologist and himself a charter member of the Lunar Society and an archetypical member of the British Industrial Enlightenment, complained in 1800 that Agriculture and Gardening had remained only Arts without a true theory to connect them. For details about Darwin, see especially McNeil, *Under the Banner*; and Uglow, *Lunar Men.*

[147] George Campbell, an important representative of the Scottish Enlightenment noted that "All art [including mechanical art or technology] is founded in science, and practical skills lack complete beauty and utility when they do not originate in knowledge" (cited by Spadafora, *Idea*, p. 31).

[148] Heilbron, "Introductory Essay," p. 5. This tradition, of course, goes back in a sense to Newton and is central to the methodologies of mid-eighteenth-century chemists such as William Cullen and Joseph Black, who insisted on separating empirical knowledge and theoretical explanation—and often did little of the latter.

Dalton's atomic weights, created a pragmatic and useable set of tricks and techniques that soon enough found industrial and other applications, yet did not hypothesize about the deep structure of matter and why the observed regularities were in fact true.[149]

Once such knowledge had been established and found to be helpful, it needed to be made available to the men in the workshops. From the widely felt need to rationalize and standardize weights and measures, to the insistence on writing in vernacular languages, to the launching of scientific societies and academies, to the construction of botanical gardens by enthusiasts such as Georges-Louis Buffon and Joseph Banks to teach the knowledge of plants, to that most paradigmatic Enlightenment triumph, the *Grande Encyclopédie*, the notion of the diffusion and accessibility of shared knowledge found itself at the center of attention among intellectuals.[150] Taxonomies and classifications were invented to organize and systematize the new facts gathered, and new forms of mathematical and chemical notation were proposed to standardize the languages of science and make propositional knowledge more accessible. To understand these languages, it was realized that increased technical and mathematical education was required, and mathematics teaching and research expanded from the establishment of chairs in mathematics in the Scottish universities in the late seventeenth century to the founding of the *école polytechnique* in 1794.[151]

To summarize, then, the *philosophes* realized that, in order for useful knowledge to be economically meaningful, low access costs were crucial and useful knowledge should not be confined to a select few but should be disseminated to those who could put it to productive use. Some Enlightenment thinkers believed that this was already happening in their time: the philosopher and psychologist David Hartley believed that "the diffusion of knowledge to all ranks and orders of men, to all nations, kindred and tongues and peoples . . . cannot be stopped but proceeds with an ever accelerating velocity."[152] Diffusion needed help, however, and much of the

[149] Lundgren, "Changing Role," pp. 263–64.

[150] See especially Headrick, *When Information,* pp. 142–43. Daniel Roche (*France*, pp. 574–75) notes that "if the *Encyclopédie* was able to reach nearly all of society (although . . . peasants and most of the urban poor had access to the work only indirectly), it was because the project was broadly conceived as a work of popularization, of useful diffusion of knowledge." The cheaper versions of the Diderot-d'Alembert masterpiece, printed in Switzerland, sold extremely well; the Geneva (quarto) editions sold around 8,000 copies and the Lausanne (octavo) editions as many as 6,000.

[151] See Jacob, "Putting Science."

[152] Hartley, a deeply religious man, made this point in the context of the diffusion of Christian beliefs, but then added that "the great increase in knowledge, literary and philosophical, which has been made in this and the two last centuries . . . must contribute to promote every great truth . . . the coincidence of the three remarkable events, of the reformation, the invention of printing, and the restoration of letters . . . deserves particular notice here." See Hartley, *Observations*, p. 528.

Industrial Enlightenment was dedicated to making access to useful knowledge easier and cheaper.[153] Intellectual factors never operate alone; institutional change was equally necessary. The importance of property rights, incentives, factor markets, natural resources, law and order, market integration, and many other economic elements is not in question. But without an understanding of the changes in attitudes and beliefs of the key players in the growth of useful knowledge, the technological elements will remain inside a black box.

QUANTIFYING THE ENLIGHTENMENT

To quantify the Enlightenment seems to violate Einstein's dictum that not everything that counts can be counted and that not everything that can be counted counts. Yet it would be useful to get a measure of the quantitative dimensions of the growth of the Enlightenment as an intellectual movement and to get a sense of the degree to which this was a local or a continent-wide phenomenon.[154] It also might be useful to examine the argument that the Industrial Revolution and technological progress were independent of the Enlightenment because of the widely repeated belief that France was the *locus classicus* of the Enlightenment whereas Britain was the cradle of the Industrial Revolution, and the two were separate, perhaps even orthogonal, historical developments.[155] The Enlightenment, unlike the Middle Ages, was not a concept invented by historians many centuries later, and while in 1784 Kant could note that the "age of Enlightenment" in which he lived was not yet "an Enlightened age," it was a concept that contemporaries were aware of. Nonetheless, historians today are better positioned to assess where the Enlightenment was of substantial importance. To derive a measure of this, I have relied on the recently published *Encyclopedia of the Enlightenment*. To count the importance of the Enlightenment, every geographical item (country, city, region, etc.) in the index was compiled and weighted by the number of lines devoted to it.[156] In Table 1,

[153] The best summary of this aspect of the Industrial Enlightenment was given by Diderot in his widely quoted article on "Arts" in the *Encyclopédie*: "We need a man to rise in the academies and go down to the workshops and gather material about the [mechanical] arts to be set out in a book that will persuade the artisans to read, philosophers to think along useful lines, and the great to make at least some worthwhile use of their authority and wealth."

[154] A few quantitative assessments exist, though it is not clear how they were arrived at. Thus Richard Herr has estimated that less than 1 percent of the Spanish population "welcomed" the Enlightenment, a tenth as many as in France. See Herr, *Eighteenth-Century Revolution*, pp. 198–200.

[155] For a devastating rebuttal to the first of these two statements, see Porter, *Creation*. For a qualification of the latter, see Mokyr, "Long-term Economic Growth."

[156] Kors, ed., *Encyclopedia*. The procedure followed the extensive index in vol. 4. If an essay on a general topic mentioned a country or region, we counted the lines that discussed that area only. If an article was devoted to a geographical concept (e.g., "Scandinavia" in vol. 4, pp. 20–25) we

I include two measures of the Enlightenment: an exclusive measure that counts only the number of lines that mention a country (e.g., "England") and an inclusive measure that counts both measures of a country and of regions in it (e.g., includes both "Italy" and "Tuscany"). The latter count has the advantage of including areas that would be underrepresented otherwise because they were only geographical and not political concepts in eighteenth-century Europe, but it contains some measure of double counting. The data in no way represent a scientific measure of anything except the editorial judgment of a group of modern enlightenment scholars (mostly Americans), but as such it provides us with at least a rough estimate of the regional distribution.[157]

The striking thing about Table 1 is, of course, that France's alleged supremacy in the enlightenment movement is not confirmed. Leaving out North America (which may well be biased by the fact that so many of the contributors are North Americans and the publisher is in New York), the image of Table 1 is that Britain and the Low Countries represent a higher level of the Enlightenment than a group of Western Continental countries that includes Germany, Scandinavia, Central Europe, and in which France occupies a less than overwhelming middle position. The importance of France is reflected in the fact that Paris (991 lines) is more heavily mentioned than any other town, but British towns between them covered more lines (London, Glasgow, and Edinburgh alone had 1,168), and France's population was three times Britain's in 1750. Adding the mentions of cities does change the numbers a bit (and worsens double counting if we add lines that mention a town to those that mention a country), but does not seriously change the overall picture.

The *Encyclopedia* index is of course biased and flawed in many other ways; the many references to "Greece" clearly refer to ancient Greece rather than indicate a hitherto unknown flourishing of the enlightenment in Ottoman-occupied Greece.[158] It is in no case an index that makes any

counted all the lines in that article. The article on "academies" includes a subheading on "Scandinavia" (vol. 1, pp. 18–19) which was then counted in its entirety. The article on "Education, reform" (vol. 1, p. 385) has a three line sentence that mentions Scandinavia, as well as France, England, and Scotland; those three lines were then entered for all four countries.

[157] Of the nine members of the board of editors, six are affiliated with universities in the United States, one in Canada, one in Ireland, and one in France. The composition of the board, however, cannot be accused of anti-French bias, as two of its American members are noted experts on eighteenth-century France and the French revolution. In that limited sense it is a more unbiased source to study the spread of the enlightenment than Delon, ed., *Encyclopedia*, which is written by a preponderant majority of French scholars. The Delon volumes, in any case, did not have an index that was useful for our purpose, so no direct comparison could be made.

[158] Some of these towns reflect topics of classical rather than eighteenth-century interest, e.g., the 174 lines devoted to Pompeii and Herculaneum or the 31 devoted to Sparta. Neither of those were included.

TABLE 1
GEOGRAPHICAL DISTRIBUTION OF ENLIGHTENMENT CONCEPTS AS REFLECTED IN THE *ENCYCLOPEDIA OF THE ENLIGHTENMENT*
(lines per million of 1750 population)

Country	Lines Counted (exclusive)	Lines Counted (inclusive of regions)	Lines Counted (inclusive of regions and urban)	Enlightenment Index (exclusive)	Enlightenment Index (inclusive of regions only)	Enlightenment Index (inclusive of regions and towns)
France	2,065	2,085	3,145	86	86.8	131
England	2,348	2,362	3,138	391.3	393.7	523
Scotland	701	709	1,207	701	709	1,207
Ireland	210	210	224	70	70	75
Germany	1,618	1,863	2,389	107.9	124.2	159
Netherlands	1,042	1,066	1,236	245.2	250.8	291
Switzerland	471	471	716	314	314	477
Scandinavia	344	436	789	116.3	208	210
Italy	503	700	1600	33.5	46.7	106
Spain	689	689	706	72.5	72.5	74
Portugal	264	264	264	117.3	117.3	117
Austria	391	407	483	142.2	148	175
Hungary	253	253	253	126.5	126.5	126
Poland	435	435	435	62.2	62.2	62
Russia	762	817	831	29.3	31.4	32
Balkans	17	17	17	2.1	2.1	2.1
Greece	282	282	282	161.1	161.1	161
Latin America	448	608	611	32.6	44.2	44.4
North America	712	1,717	1,903	323	780.4	865
Ottoman Emp.	182	235	238	7.6	9.8	9.9

Note: For details on the computation, see footnote 156.

claims to cardinality. It would be absurd to claim that just because Scotland has nine times the index that France had, it in any shape or form could claim to be nine times more enlightened than France. But even if we do not deflate by population (a process that appreciably weakens France's relative position), the ordinal values of the index suggest that a Francocentrist position in the Enlightenment seems untenable: even in *absolute* terms (which is what may have counted). Britain still exceeds France, and Germany is but a hair behind. Perhaps, however, the real objection to this measure is that it pertains to the *Enlightenment* as commonly used, and thus obviously does not deal with the *Industrial* enlightenment as defined above. For the purposes of technological change, we may be less concerned with the philosophical or political concerns that dominated much Enlightenment thinking and instead focus on the growth of science and other forms of useful knowledge, their application to industry and agriculture, and the diffusion of best-practice techniques among the population of artisans and farmers.

To capture at least the first of these, we can look at the geographical incidence of scientific and technological periodicals, the publication of which became increasingly associated with the European enlightenment in the eighteenth century.[159] A useful source is the list of all scientific and technical journals published in Europe between 1600 and 1800. David Kronick meticulously compiled this difficult and often confusing source, and whereas some aspects of his work and conclusions bear re-examination, much of what is to follow is indebted to his data collection.[160] An analysis of these journals is inevitably deficient in that it disregards the number of readers of these periodicals and the number of copies printed and circulated, and does not assess the content beyond Kronick's label.[161] Yet it allows us to measure publication dates, place, and the general topic of the periodical. As such, it gives us a rough but instructive indicator of the "degree" of industrial enlightenment prevalent.[162] As Kronick notes, "by far the largest part of this literature represented not original research or contributions but a derivative form of journalism which served the purpose of the dissemination of information."[163] That kind of publication is of course precisely descriptive of an activity that was primarily aimed at a reduction of access costs. There can be little doubt that the importance of periodicals as a means of access to useful knowledge underwent a revolution during the age of Enlightenment.[164]

There are three major findings to report. The first, unsurprisingly, is that the number of new journals published accelerated rapidly after 1650; indeed, the new journals published in the last three decades of the eighteenth century account for 68 percent of all journals published in this period. This is demonstrated clearly in Figure 1. Second, the distribution by topic, roughly defined, shows some interesting changes during this period. On the whole, Science and Medicine each account for about 30 percent of all

[159] See especially McClellan, "Scientific Journals."

[160] Kronick, *Scientific and Technical Periodicals* and *History*

[161] At times, periodical titles could be misleading. The *Ladies' Diary,* edited by the engineer, surveyor, and mathematician Henry Beighton, was full of essays on mathematical and physical topics including his famous 1718 table on the capacity of the Newcomen engine cited previously. The *Gentleman's Diary*, edited by Thomas Peat between 1756 and 1780, was similarly largely devoted to the solution of mathematical problems See Musson and Robinson, *Science*, p. 47; and *Dictionary of National Biography*, vol. 15, p. 625.

[162] The analysis here differs somewhat from the one Kronick conducts himself in that I make no distinction between "substantive" journals, "society proceedings," and journals of abstracts and reviews. My main purpose here is to illustrate the decline in access costs, and journals that published abstracts and reviews served a similar purpose.

[163] Kronick, *History,* p. 239.

[164] Gascoigne's sample of the most important scientists born in the period 1665–1780 shows that a full 65 percent of them published in scientific journals, though there is no real way of telling whether such journals were their main channel of communication. The percentages rises steeply over time: for scientists born in 1600–1609 it is 17 percent, for those born in 1700–1709 it is 65 percent and for those born in 1770–1779 it is 85 percent. These statistics entirely exclude engineering, medical, and agricultural journals. See Gascoigne, *Historical Catalogue,* p. 92.

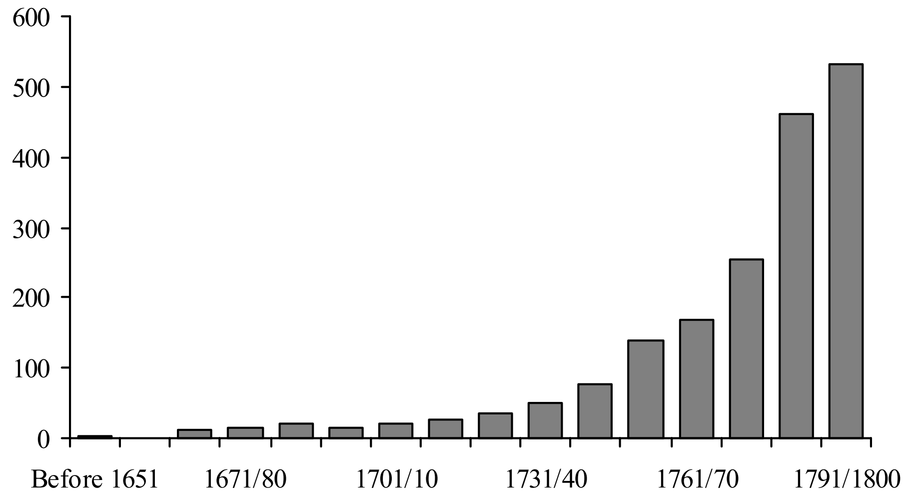

FIGURE 1
SCIENTIFIC PERIODICALS BY YEAR OF FIRST APPEARANCE

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

journals, and this total remains fairly stable over the entire period (Figure 2). What is remarkable is the steep rise in the journals devoted to political economy and social science, from essentially nil to a substantial number in the second half of the eighteenth century, especially in Germany where interest in political economy and the science of government was substantial. The same is true for journals dedicated to technology and engineering (including agriculture). This increase comes at the expense of more general and philosophical journals, whose share declines despite an increase in absolute numbers.

The geographical distribution of journals shows an interesting pattern. Europe as a whole seems to divide into three regions: areas with a high rate of publication relative to population (Scandinavia, Low Countries, Switzerland), an intermediate group including France and Britain, and the expectedly low-intensity countries such as Spain and Austria, not to mention Russia. In absolute terms, German periodicals had a large advantage, but their mean life expectancy was only about seven years, as opposed to the 16 or 17 years for the average periodical in Britain or France.[165] Some areas do surprisingly poorly: Scotland counts only ten periodicals, Belgium only seven. To some extent this reflects their dependence on

[165] This is pointed out by Kronick, *History,* pp. 86–87. Elsewhere (p. 160) he notes that in Germany "the lack of political centralization was reflected in the large number of regional journals, every intellectual center or University town in Germany had its own journal of learned and scholarly news."

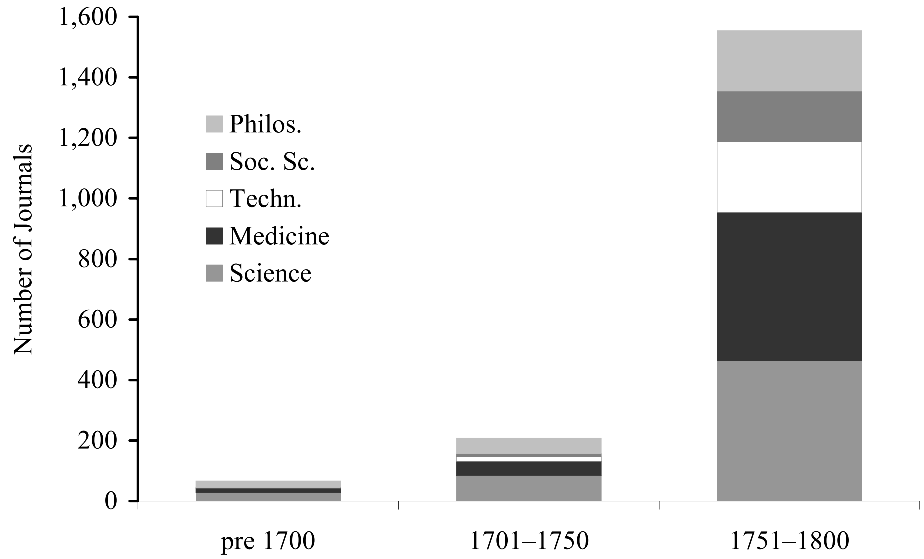

FIGURE 2
NEW SCIENTIFIC JOURNALS, BY GENERAL SUBJECT AND DATE

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

periodicals coming in from elsewhere. All the same, Scotland outranks France in per capita weighted publications (Figure 3), but both are considerably behind the Netherlands and Switzerland, two countries with flourishing publishing industries (catering no doubt in part to foreign markets). The distribution of new journals by subject matter does not show Britain as in any way unusual; the only odd phenomenon is the very high proclivity of Scandinavian countries for science and the high frequency of medical and social science journals in Germany (Figure 4). As far as technology, agriculture, and engineering are concerned, remarkably enough France was in the lead. None of these results are materially different whether we count journals by first appearance only or whether we weight them by years of survival, except that German periodicals become less important as average periodical life in Germany was substantially shorter.

Finally, to get a better quantitative handle on the development of the formal institutions that were meant to reduce access costs, I utilize a database that relies heavily on the website "Scholarly Societies" collected by the University of Waterloo.[166] The Waterloo database used covers 200 years (1600–1799) and contains 236 societies founded in Europe in those years (Figure 5). As the database is still incomplete, it was supplemented

[166] http://www.scholarly-societies.org. The database was put together by its editor Jim Parrott. I am grateful to Mr. Parrott for his advice and assistance.

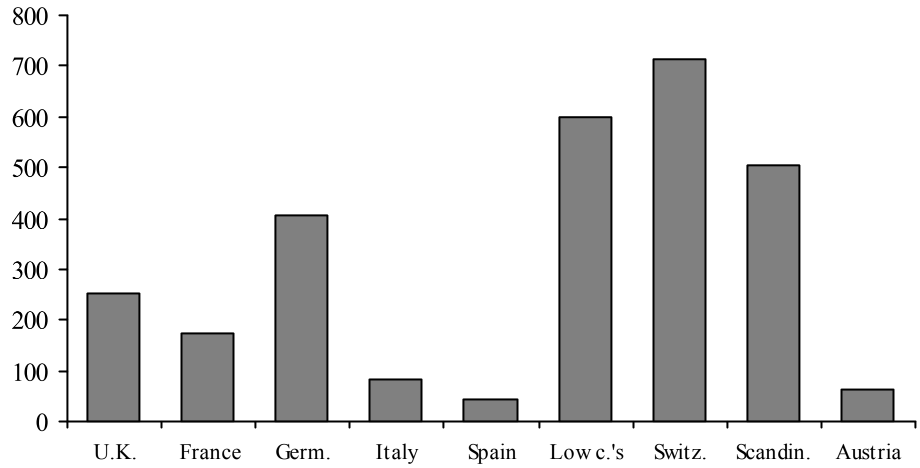

FIGURE 3
NUMBER OF SCIENTIFIC JOURNALS PER CAPITA, WEIGHTED BY YEARS OF PUBLICATION

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

by a set of standard works that deal with scientific academies and societies, yielding a total of 349 societies.[167] There is no presumption that the database is complete, though it is likely that any omitted formal societies were of tertiary importance. Counting such organizations without weighting is of course a crude procedure. Yet the movement over time between 1600 and 1800 and the differences in cross section display three trends, all of which are indicative of the impact of the Industrial Enlightenment on European intellectual life. First, as shown by Figure 6, there is a clear time trend: after an efflorescence in the 1650s and 1660s there is a slowing down in the founding of these learned societies until the 1730s, when the phenomenon takes off. Secondly, as Figure 7 shows, learned academies and societies were a Continent-wide phenomenon. Indeed, the advantage of the British Isles in learned societies is not particularly striking by comparison with economically backward Italy and Germany: in the two centuries before 1800, Britain accounted only for 30 societies whereas France had 54 and Germany and Italy counted 31 each. Yet in the second half of the eighteenth century Britain experienced a flourishing of intellectual life as measured by the number of formal learned societies established there. At the same time, a veritable explosion occurred in the "small countries" of Europe (Iberia, Scandinavia, Low Countries, and Switzerland). Deflating by population, as in Figure 7, yields a somewhat different picture. Western

[167] Among those are Lowood, *Patriotism*; McClellan, *Science Reorganized*; Daniel Roche, *Le Siècle des Lumières*; and Cochrane, *Tradition.*

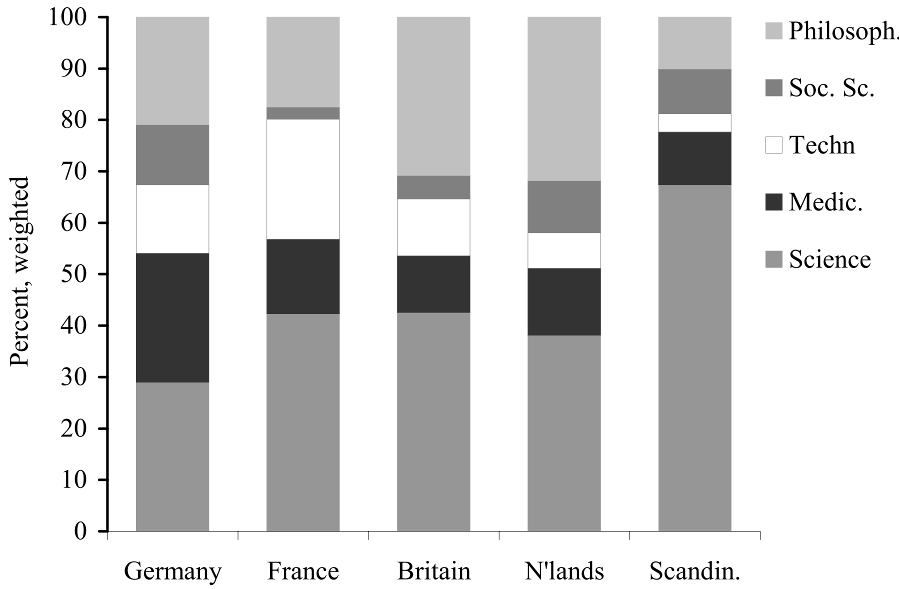

FIGURE 4
SUBJECT AREA OF NEW PERIODICALS, BY COUNTRY

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

Europe's small countries and Germany clearly took the lead in this kind of intellectual activity after 1750, with Italy and to a lesser extent France falling behind. Within the "small countries," the literate nations in Scandinavia and the Netherlands experienced a veritable outburst of such societies after 1750. Third, as Figure 6 shows, there was a considerable growth in the number of societies interested primarily in applied and science-oriented nature after 1750, although all three categories experienced considerable growth in the second half of the eighteenth century. As can be seen from Figure 6, Britain had perhaps a slight advantage in terms of the relative importance of societies classified as "scientific," but this difference is far from overwhelming.

Such numbers, taken at face value, are misleading. In Italy and Germany many of the local societies reflect the political fragmentation of the countries, in which local aristocrats or magistrates had to display their independence, accounting for some provincial societies in small towns such as Cortona, Palermo, and Rovereto. Yet similar provincial institutions are found in France and Spain. It is also true that some societies were of an ephemeral nature and duplicated others.[168] One interesting finding is that

[168] A good example is the *Societas Disputatoria Medica Haunienis* (Medical Debating Society of Copenhagen), founded in 1785 as the result of a disagreement between two Danish physicians. It folded two years later.

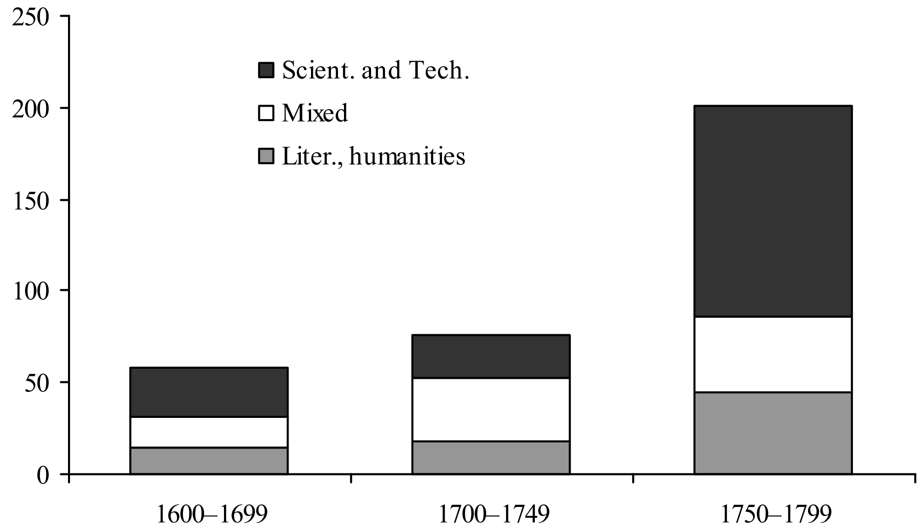

FIGURE 5
SCIENTIFIC SOCIETIES BY PERIOD AND MAIN PURPOSE

Source: See notes 166 and 167.

Figure 7 shows, oddly, that the number of societies was higher in the second half of the eighteenth century than in the previous century and a half except in Italy; this may indicate the growing importance of private, spontaneously founded scientific societies in the later period. Italian societies were predominantly established by local authorities.

To summarize these findings, two things stand out. The first is that the eighteenth century found a variety of mechanisms to reduce access costs, and that all measures we can find point to a rapid acceleration in the institutions that brought this about. Second, differences among the national styles and emphases among the main societies that later were to constitute the "convergence club" can be discerned, but most of them were secondary to their partaking in the more general movements of the Industrial Enlightenment. There is little in the quantifiable evidence to single out the Enlightenment movement in Britain as being unusual or particularly conducive to economic success. The historical factors that explain the rise of the Industrial West are thus not the same as the ones that explain Britain's leadership.

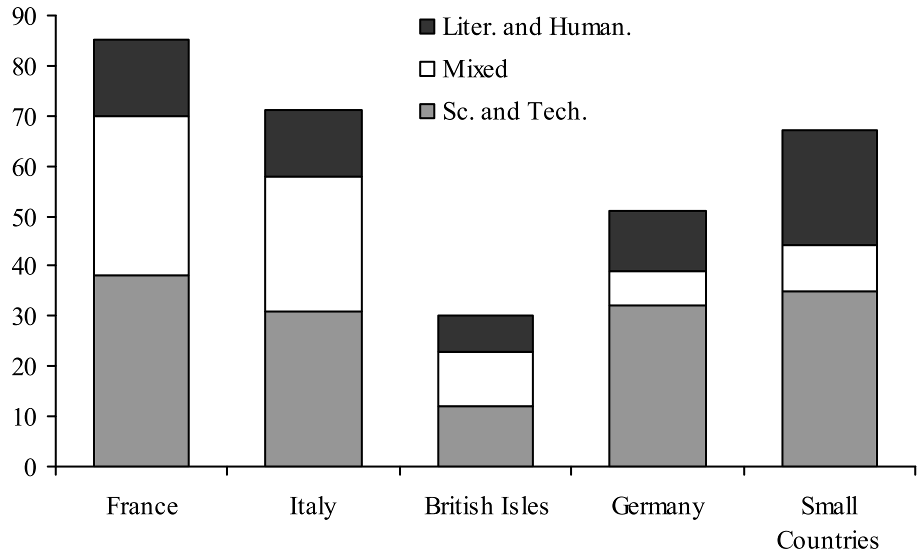

FIGURE 6
SCIENTIFIC SOCIETIES, 1600–1800, BY COUNTRY AND PURPOSE

Source: See notes 166 and 167.

CONCLUSIONS

The Enlightenment in the West is the only intellectual movement in human history that owed its irreversibility to the ability to transform itself into economic growth. It did so by fueling the engine of economic growth with the sustained supply of useful knowledge and the miraculous ability to apply this knowledge eventually to the nitty-gritty of production in the fields and workshops where the GDP is ultimately produced. It did so also by providing the economies with institutional steering wheels that on the whole prevented them from crashing the vehicle of economic growth into the trees of rent seeking, war, and other forms of destructive behavior.[169] It is safe to say that the vehicle had a few fender-benders and near misses on the way, and here and there had to swerve hard to avoid the semi-trailers of total war and totalitarianism.

The Industrial Enlightenment produced technological progress, but there was no guarantee that it would have resulted in sustained economic growth. In addition to the Baconian program, the Enlightenment produced what might best be called a doctrine of *economic reasonableness*, which became embodied in the tenets of political economy, and eventually influenced policy makers in most Western economies. Economic reasonableness

[169] On this see Mokyr, "Mercantilism."

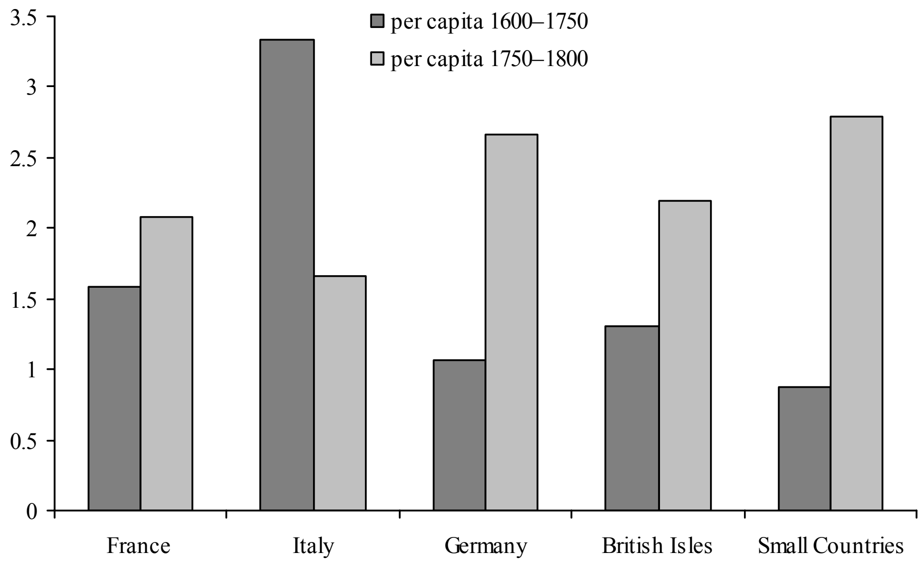

FIGURE 7
SCIENTIFIC SOCIETIES PER CAPITA , 1600–1800

Source: See notes 166 and 167.

concerned issues of political economy such as free trade, improved infrastructure, law and order's effect on commerce, and more efficient, less distortionary taxes. Above all is the Enlightenment idea that when individuals work for their own good, they normally also contribute to the welfare of society, unless they choose to engage in redistribution and rent seeking. It redefined the role of the public sphere in the economic game, pointing to the delicate balance between those who lubricate the wheels of economic activity and those who manipulate them for their own private profit. It recognized the possibility of what we might call today coordination failures and suggested policies to rectify them.

Without institutional progress to complement the technological progress, the sustainability of economic improvement would have been limited and in the end might have been frittered away and eliminated by the relentless erosion of rent seeking. Needless to say, the growth of economic reasonableness was far less monotonic and irreversible than technological progress. Opportunistic and selfish behavior did not go away simply because Enlightenment intellectuals denounced it. The cosmopolitan, internationalist subtext of the most progressive wings of the Enlightenment was constantly struggling with the traditions of mercantilism and the instincts of economic rivalry and political hostility between the major European powers. As long as the Enlightenment was a movement of elites, who saw themselves as members of the Republic of Letters, it could maintain a cosmopolitan character. By its own logic, however, as it spread to larger and larger circles, nationalist and romantic sentiments inevitably clashed with the enlightened internationalist instincts of the *philosophes*, threatening the great synergy between institutional and technological elements of the Enlightenment.

The interactions between these elements is of course complex and makes positive identification of causal factors difficult. The impact of enlightenment thought on institutional reforms took place with long lags and over a very long period of time.[170] Moreover, such economic liberalization—not to be confused with political liberalization and franchise extension—took a long time to affect output growth. In any event, its impact was largely in what it prevented, not in what it caused. As such the exact effects may be hard to trace with much accuracy. Indeed, the great irony of the European Enlightenment is that the attempts by France to adopt more "enlightened institutions" led to a prolonged military conflict with the nation that had already adopted many of those. In the process, enlightenment ideas were put on the back burner. After 1815, however, the *Pax Britannica* heralded in a new culture of peace and trade. It, too, was not to last. In the best Hegelian traditions, it created forces that challenged it. Nationalism, protectionism, and economic *étatism* were responses to the Enlightenment, not an inevitable corollary. The Enlightenment itself can by no stretch of the imagination be held responsible for the twentieth-century horrors that Theodore Adorno and Max Horkheimer and their modern-day postmodern epigones such as John Gray blame them for.[171] One of the oddest phenomena in modern historiography, indeed, are the vitriolic and nasty attacks on the Enlightenment, which perversely is being blamed for modern-day Barbarism but not given credit for bringing about modern-day prosperity.[172]

The central fact of modern economic growth is the ultimate irreversibility of the accumulation of useful knowledge paired with ever-falling access costs. As long as knowledge was confined to a small number of specialists with high access costs for everyone else, there was a serious risk that it could be lost. Many of the great inventions of China and Classical

[170] Indeed, John Nye has argued that the impact of political economy on trade liberalization in Britain has traditionally been misdated and took place much later than hitherto supposed. Nye, *Wars*.

[171] Horkheimer and Adorno, *Dialectic*. Gray, *Enlightenment's Wake.*

[172] This revulsion has deep philosophical roots in the works of Nietzsche and Heidegger, but the usefulness of the critique to historians interested in economic progress is doubtful. Even left-wing historians are embarrassed by notions that the Enlightenment inevitably led in some way to male-domination, imperialism, totalitarianism, environmental degradation, and exploitation. Eric Hobsbawm notes with some disdain that this literature describes the Enlightenment as "anything from superficial and intellectually naive to a conspiracy of dead white men in periwigs to provide the intellectual foundation for Western Imperialism." See Hobsbawm, "Barbarism," pp, 253–65.

Antiquity were no longer available to subsequent generations. The decline in access costs meant that knowledge was spread over many more minds and storage devices, so that any reversals in technological progress after the Industrial Revolution were ruled out. If the continued growth of the West was ever in danger, it came from the imbalance between rapid progress in the accumulation of useful knowledge and the more halting and ambiguous changes in supporting institutions.

Such an approach to modern growth would imply that the differences between the nations of the West should be less important than their basic commonalities. The point is not so much that there were no national differences in the institutions and culture that generated useful knowledge in France, Germany, or Britain, as that when the knowledge was accepted, it was readily diffused within the world in which the Enlightenment had taken root through periodicals, translations, international exhibitions and conferences, and personal communications. Stressing national differences in style and emphasis within the West is to miss the fundamental unity of the world affected by this intellectual movement. In this view of the Industrial Revolution, Britain had a first-mover advantage that was extended by the political upheavals of the Revolutionary and Napoleonic era, but the convergence of technology and income in the later nineteenth century was inherent in the nature of the movement that generated economic growth.

All this leaves in the middle what explains the Enlightenment itself. It surely was no autonomous shock like the Black Death or a Mongol invasion that altered the course of European history without requiring an explanation itself. The Enlightenment had roots in the commercial capitalism of the later middle ages and the sixteenth century. Many of the elements of a progressive society—such as individualism, man-made formal law, corporatism, self governance, and rules that were determined through an institutionalized process (in which those who were subject to them could be heard and have an input)—already existed in late medieval Europe.[173] Pre-1750 economic growth created the economic surpluses that made it possible for a considerable number of people to move to urban areas and nonagricultural occupations, including by becoming full-time intellectuals. Yet despite the stimuli of the Great Discoveries and the technical advances of the fifteenth century, Renaissance Europe did not generate anything like modern growth. Many highly commercial societies of the past, for one reason or another, failed to switch from trade-based growth to technology-based growth. Even the great Dutch prosperity of the seventeenth century dissipated and petered out in the end.

[173] Greif, *Institutions*, chap. xiii–17.

In order for commercial expansion and Smithian growth to transform themselves into a self-sustaining process of rapid growth something more was required. The ultimate economic significance of the Enlightenment was to bring this about. But whence the Industrial Enlightenment itself? Understanding its intellectual origins is a daunting task. Of the many explanations that have been proposed, it is worth mentioning a powerful argument made by the late B. J. T. Dobbs that when a period of relative stability settled on Europe's social and political life in the later seventeenth century, hopes for an imminent millennium were becoming dimmer, and open useful knowledge with utilitarian purposes (inspired by Bacon) replaced the more mystical and secretive activities of the late Renaissance alchemists. It is also plausible that an impulse to the Industrial Enlightenment came from below, from artisanal writers writing about mechanical arts such as mining and architecture in the previous centuries.[174]

Yet such purely intellectual explanations need to be complemented by institutional ones. In coming to grips with the oversimplified question of "why there was a European Enlightenment," a starting point is to ask not so much why some people emerged who elucidated ideas and policies we now consider to be "enlightened," as much as why these people succeeded. It is highly probable that men and women with novel ideas emerged outside the West, and would have been part of an Islamic Enlightenment or a Chinese Enlightenment, had these grown to become movements of historical importance.[175] Europe differed in that the seeds of innovation sprouted and flourished. In part, therefore, the triumph of the Enlightenment was contingent, the result not of sheer accident or random variables as much as of a set of political and social struggles that could have gone the other way. The counter-reformation led by the reactionary forces of Spain was de-

[174] Dobbs, "From the Secrecy." Long, *Openness*.

[175] It could well be argued that seeds of an Enlightenment were sown by Fang Yi-Chih (1611–1671), the author of a book meaningfully entitled *Small Encyclopedia of the Principles of Things*, which discussed potentially useful forms of propositional knowledge such as meteorology and geography. He was a harbinger of the eighteenth-century school of *kaozheng,* or school of "evidentiary research," which sounds promising until we realize that it was primarily interested in linguistics and historical studies, "confident that these would lead to greater certainty about what the true words and intentions of China's ancient sages had been and, hence, to a better understanding of how to live in the present" (Spence, *Search for Modern China,* p. 103). Similarly, the great scholar Tai Chen who was "a truly scientific spirit . . . whose principles hardly differed from those which in the West made possible the progress of the exact sciences. But this scientific spirit was applied almost exclusively to the investigation of the past" (Gernet, *History*, p. 513). The vast efforts of the Chinese Ch'ing emperors in publishing encyclopedias and compilations of knowledge under K'ang Chi and Qian Long, above all the massive *Gujin tushu jicheng* compiled by Chen Menglei and published in 1726 (one of the largest books ever produced with 10,000 chapters, 800,000 pages and 5,000 figures) indicate an awareness of the importance of access cost. It is meaningful, however, that Chen was arrested and deported (twice), that his name was removed from the project, and that the entire project was done under imperial auspices. Altogether about 60 copies were made of it, a number that pales in comparison with the 25,000 copies sold of the *encyclopédie.*

feated in a set of wars that left Europe bleeding and divided, but that also marked a sizeable part of the Continent that was open to fresh ideas introduced in the competitive intellectual marketplace.[176]

If so, there was nothing inevitable or inexorable about modern economic growth. Much like the emergence of *homo sapiens sapiens* in the Pleistocene after some 60 million years of mammal development, and not, say, in the long period (50 million years) between the Eocene and the end of the Miocene, a long period of "prehistory" occurred before the dramatic phase transition that changed the face of the planet forever. There is nothing in evolutionary theory that makes the rise of homo sapiens inevitable or its precise timing an explicable phenomenon. Although metaphors may mislead, the parallel points to the possibility that radical and irreversible historical change may occur as a contingency. That does not absolve us from the possibility of thinking about its causes—contingency does not mean randomness.

To understand the origins of the triumphs of Enlightenment thought, we must understand the victory of skepticism and rebellion against authority in the centuries of early modern Europe. Aside from the obvious cases of Luther and his fellow reformers, we may point to the growing proclivity of Europeans to question traditions that had ruled during centuries in which original scholarship had rarely consisted of more than exegesis and commentary on the classics.[177] Of course, Francis Bacon himself was a leader among those skeptics.[178] Criticism of authority was prevalent in every society, no matter how reactionary and repressive, but the question of essence must be what explains the survival and success of this movement. Here, part of the answer must be sought in the system of political fragmentation and countervailing power in which those who contested the "truth" as perceived by the status quo could normally find protection against the

[176] See Lebow, Parker, and Tetlock, eds., *Unmaking the West*.

[177] Illustrative of this inclination is the career of Lorenzo Valla (1407–1457). Humanist, philologist, and professional rebel, most famous for his demonstration that the "Donation of Constantine" was a forgery, he attacked other sacrosanct icons such as Cicero's style, Livy's history, and St. Thomas's theology. He seemed to "delight in challenging established authorities" and his work was "an attempt by a humanist intellectual to change rhetorical study from a process that involved the 'passive' acquisition of erudition into an 'active' discipline that would be capable of engaging practical problems" (Connell, "Introduction," pp. 1, 6).

[178] In an unpublished work, oddly entitled *The Masculine Birth of Time,* Bacon launched a sharp and severe attack on Aristotelian philosophy. The entire canon of classical thought, from Plato to Hippocrates and from Thomas Aquinas to Peter Ramus was denounced. Their sin was, above all, moral: they were, in Bacon's view, indifferent to the mastery of man over nature, which was the only way to alleviate the plight of mankind "with new discoveries and powers." See Farrington, *Francis Bacon*, pp. 62–68. Ramus (1515–1572) himself, an influential Calvinist philosopher, had been similarly disrespectful of accepted orthodoxy (his 1536 thesis was entitled *Everything that Aristotle Taught is False*), but had the bad fortune to find himself in Paris on St. Bartholomew's Day in 1572, where he was murdered.

persecution they could face.[179] What is unique in the European experience is not what happened to Jan Hus and Giordano Bruno, but that the same fate was not ordained for the many others who shamelessly slaughtered sacred cows in natural philosophy and metaphysics.[180] Skepticism, rebelliousness, and disrespect were as much the taproots of innovation as economic incentives. In the European environment, these sentiments survived largely because their propagators were able to play different political units, as well as spiritual and temporal authorities, against one another. Multicentrism made it possible for original thinkers to move between different regions and spheres of influence, to seek and change protectors and patrons. When some centers were destroyed by political events, the center of gravity shifted elsewhere.[181] Moreover, competition by courts and patrons of science for the "superstars" led to informational and reputational difficulties that in the end may have helped bring about the system of open science.[182] Political fragmentation had its costs, of course, and it was not a sufficient condition for intellectual innovation. All the same, what made the European Enlightenment succeed, was the combination of political multicentricity and sharpening intellectual competition thanks to falling access costs. It did not succeed everywhere, but it did not have to. By 1680 or so this skepticism, though by no means unchallenged, had become sufficiently widespread to become irresistible. It evolved into an intellectual *movement*.

In the end, the Enlightenment delivered perhaps less than what the more naive idealists of the Enlightenment had hoped for. The more ambitious and optimistic schemes of such *philosophes* as Condorcet or David Hartley are not to be confused with the whole of Enlightenment thought and work in the eighteenth century.[183] Humphry Davy, by 1802, had no more illu-

[179] Valla himself was protected by King Alphonso of Naples from the recriminations of Pope Eugenius V and the Naples Inquisition. So fragmented were the politics of Europe at the time that Eugenius's successor, Nicholas V, appointed him Papal secretary.

[180] The most outspoken example was the pugnacious German physician Paracelsus (1493–1541), sometimes referred to as a "medical Luther," who in 1527 publicly burned the books of Galen and Avicenna, the medical authorities he despised.

[181] Britain's supremacy in the late eighteenth century may well have benefited from the adventitious events that spared it the fate that befell the scientific and intellectual center of pre-1620 Prague. It seems not unreasonable to speculate that had the Czech Renaissance not been destroyed by the Thirty-Years War, it might have evolved into a center of a Central European Enlightenment and the innovative thrust of the eighteenth century might have had a different locational pattern. For a discussion of the intellectual glories of the Habsburg court around 1600, see Evans, *Rudolf II.* The Moravian religious leader and educational reformer Jan Amos Comenius, fleeing his native Czech lands from the Imperial forces, repeatedly found himself in politically uncomfortable circumstances and spent time in Poland, London, Paris, Sweden, and Amsterdam.

[182] David, "Patronage."

[183] Broadie has noted that the optimism of most Enlightenment "literati" was guarded and that there was no serious streak of utopianism in the Scottish Enlightenment. Broadie, *Scottish Enlightenment*, p. 39.

sions that we should "amuse ourselves with brilliant though delusive dreams concerning the infinite improveability of man, the annihilation of labour, disease, and even death . . . we consider only a state of human progression arising out of its present progression" and then added prophetically, "we look for a time that we may reasonably expect, for a bright day of which we already behold the dawn."[184] The optimists may have overestimated the ability of people to reason in many social settings, they may have been naive about the objective function that rulers and people of power and wealth were maximizing, and surely even the more cynical political thinkers such as Hume and Smith did not fully realize how strategic behavior and collective action in nonrepeated settings could lead to Pareto-dominated equilibria. The hyper-rational assumptions about the perfectibility of the human environment and the restructuring of institutions may seem ingenuous to us.

And yet the Baconian program succeeded beyond the wildest dreams of the natural philosophers and engineers who made the Industrial Enlightenment. The Enlightenment believed that human improvement could be attained through reason and knowledge. But as belief in reason has become more and more qualified in the centuries after Davy, the notion that the growth of useful knowledge is the mainspring of economic growth has proven to be an overwhelming truth. The result has been what Robert Darnton has termed "progress with a little p," distinct from the ambitious utopianism and political sentimentalism characteristic of some Enlightenment thinkers, but conforming to the economist's prosaic and sober notion that economic growth is not an undivided blessing but the best we can hope for in a second-best world.[185] It consists of the modest and incremental gains of pleasure over pain, of health over sickness, of abundance over want, of comfort over physical misery. It is what the history of economic growth is all about.

[184] Davy, *Discourse*, vol. 2, p. 323.
[185] Darnton, "Case," p. 23.

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