Knowledge, Technology, and Economic Growth

During the Industrial Revolution

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"*It is clear from the preceding that every "art" [technique] has its speculative and its practical side. Its speculation is the theoretical knowledge of the principles of the technique; its practice is but the habitual and instinctive application of these principles. It is difficult if not impossible to make much progress in the application without theory; conversely, it is difficult to understand the theory without knowledge of the technique. In all techniques, there are specific circumstances relating to the material, instruments and their manipulation which only experience teaches*."

Denis Diderot, article on "Arts" in the *Encyclopédie*

Introduction

Can we "explain" the Industrial Revolution? Recent attempts by leading economists (Lucas, 1998; Hansen and Prescott, 1998; Acemoglu and Zilibotti, 1997) focus more on the issue of timing ("why did it happen in the eighteenth century") than the issue of place ("why Western Europe?"). Both questions are equally valid, but they demand different types of answers. In what follows, I will answer the first question only, although the ideas used here can readily be extended to the second. The answer for the timing question is to link the Industrial Revolution to a prior or simultaneous event that clearly was not caused by it. Rather than focus on political or economic change that prepared the ground for the events of the Industrial Revolution, I submit that the Industrial Revolution's timing was determined by intellectual developments, and that the true key to the timing of the Industrial Revolution has to be sought in the scientific revolution of the seventeenth century and the enlightenment movement of the eighteenth century. The key to the Industrial Revolution was technology, and technology is knowledge.

The idea that changes in human knowledge are a crucial ingredient in economic growth seems so self-evident as to leave elaboration unnecessary, were it not that with some notable exceptions – especially the work of the Stanford school embodied by the work of Nathan Rosenberg and Paul David – economists actually rarely have dealt with it explicitly. Even the "New Growth Theory," which explicitly tries to incorporate technology as one of the variables driven by human and physical capital does not try to model the concept of knowledge and its change over time explicitly. Yet nobody would seriously dispute the proposition that living standards today are higher than in the eleventh century primarily because we know more than medieval peasants. We do not say that we are smarter (there is little evidence that we are) and we cannot even be sure that it is because we are better educated (though of course we are). The central phenomenon of the modern age is that as an aggregate we know more. But who is "we"? What is meant by "know" and what kind of knowledge really matters?

In what follows I will sketch a rough outline of what a theory of knowledge of interest to economic historians should look like and then apply it to the issues around the sources of the Industrial Revolution in Britain. The central conclusion from the analysis is that economic historians should re-examine the epistemic roots of the Industrial Revolution, in addition to the more standard economic theories explaining it that focus on institutions, markets, geography and so on. In particular, the interconnections between the Industrial Revolution and those parts of the Enlightenment movement that sought to rationalize and spread knowledge may have played a more important role than recent writings (e.g. the essays in Mokyr, 1998c) have given it credit for. This would explain the timing of the Industrial Revolution following the enlightenment and -- equally importantly -- why it did not fizzle out like similar bursts of macroinventions in earlier times. It might also help explain why the Industrial Revolution took place in Western Europe (although not why it took place in Britain and not in France or the Netherlands).

A Theory of Useful Knowledge.

To start with, we need to define *useful* knowledge. The term "useful knowledge" originates with Kuznets (1965, pp. 85-87) and I will use it here to describe knowledge (that is to say, beliefs) about *natural* phenomena.[1] The essence of production technology is the manipulation of nature for our material purposes. Hence useful knowledge deals with natural phenomena that *potentially* lend themselves to manipulation such as materials, energy, and living beings.[2] There is some arbitrariness in this, of course, since it leaves somewhat ambiguous whether psychological, anthropological, or sociological knowledge, which presumably lends itself to the manipulation of people by other people, should be included. It could also be argued that *economic* knowledge (e.g. about prices or rates of return on assets) should be included since it is necessary

[1]Kuznets confined his set to "tested" knowledge that is potentially useful in economic production. In what follows below, this definition is far too restrictive. There exists of course no universally accepted definition of what "testing" means; any testing procedure is a social convention at the time of convention. Instead I am relying below on a more relativistic concept of "tightness" of knowledge.

[2]"Production" should be taken to include household activities such as cooking, cleaning, childcare and so forth, which equally require the manipulation of natural phenomena and regularities.

for efficient production and distribution. For the present purposes I will largely depend on a narrower definition including *natural* phenomena only, so as to concentrate on technological issues.

Knowledge resides either in people's minds or in storage devices from which it can be retrieved. From the point of view of a single agent, another's mind is a storage device as well. The total useful knowledge in a society can then be defined simply as *the union of all the pieces of useful knowledge contained in living persons' minds or storage devices*. I will call this set S. A discovery then is simply the addition of a piece of knowledge hitherto not in that set. Learning or diffusion would be defined as the transmission of existing knowledge from one individual or device to another.[3]

Useful knowledge takes two forms: one is the observation, classification, measurement, and cataloguing of natural phenomena. The other is the establishment of regularities, principles, and "natural laws" that govern these phenomena and allow us to make sense of them. Such a definition includes mathematics insofar as mathematics is used to describe and analyze the regularities and orderliness of nature.[4] This distinction, too, is not sharp, since many empirical regularities and statistical observations could be classified as "laws" by some and "phenomena" by others. Useful knowledge includes "scientific" knowledge as a subset, but it involves a great deal more: practical informal knowledge about nature such as geography; the properties of materials, heat, plants, and animals; intuitive understanding of basic mechanics such as levers, pulleys, and cranks; regularities of ocean currents and the weather; and folk wisdoms in the "an-apple-a-day-keeps-the-doctor-away" tradition. It also includes engineering knowledge, more formal than folk wisdom and the pragmatic knowledge of the artisan, but less than science, what Edwin Layton (1974) has termed "technological science" or "engineering science" and Walter Vincenti (1990) has termed "engineering knowledge".[5] This part of S concern not so much the general "laws of nature" as much as the formulation

[3]Formally, if S is the union of all the individual sets of knowledge contained in either minds or storage devices, diffusion and learning would concern the *intersection* of these sets. The larger the number of units in all intersections, the larger the *density* of S.

[4]As Crosby (1997, p. 109) notes, "measurement is numbers and the manipulation of numbers means mathematics." The great mathematician David Hilbert is reputed to have remarked that there is nothing more useful than a good mathematical theory (cited in Casti, 1990, p. 33).

[5]A good example is the knowledge of the properties of materials, one of the cornerstones of all techniques. By the early nineteenth century, this part of material science was being analyzed by scientists who learned to distinguish between elastic strength and rupture strength. But until then, this entire S was controlled by old-fashioned engineers and carpenters who "limited themselves to instinctively measuring the influence of the differences in buildings which appear to serve a similar function" (Guillerme, 1988, p. 242). This informal, intuitive and instinctive knowledge of natural regularities and of what could and could not be done is what most of S consisted of before modern science formalized substantial portions of it.

of quantitative empirical relations between measurable properties and variables, and imagining abstract structures that make sense only in an engineering context, such as the friction-reducing properties of lubricants or thermodynamic cycle of an internal combustion engine (Ferguson, 1992, p. 11). It seems pointless, on the other hand, to argue about whether components of S are "correct" or not. Theories and observations about nature may have been of enormous practical influence and yet regarded today as "incorrect."

Evolutionary epistemology views knowledge as an entity subject to "selection" by agents. Selection has two dimensions: first, given the huge size of S, selectors have to decide which knowledge they choose to acquire themselves since they cannot acquire it all. Second, knowing is not believing. What is interesting, in addition to its practical importance, is to what extent knowledge is "tight" that is, to what extent the rhetorical conventions accepted in society persuade people that something is "true" or at least "tested." Tightness determines the confidence that people have in the knowledge and -- what counts most for my purposes -- thus their willingness to act upon it. Such rhetorical conventions vary from "Aristotle said" to "the experiment demonstrates" to "the estimated coefficient is 2.3 times its standard error." The rhetorical rules are pure social constructs, but they are not independent of how and why knowledge, including "useful" knowledge, grows over time. The actual structure of S is self-referential: a great deal of knowledge consists of knowing that something is known and knowing how to find out in case of need.

The role that useful knowledge can play in a society's technological development depends on three elements: how large is S (that is, *what* is known); how diffuse is this knowledge (*who* and *how many* know what is known); and the marginal access costs (*how much does it cost* me to find out what I do not know). A lot will depend on the efficiency and cost of access to knowledge. Although knowledge is a public good in the sense that the consumption of one does not reduce that of others, the private costs of acquiring it are not negligible in terms of time and often real resources as well. When the access costs become very large, in the limit it could be said that knowledge has disappeared.[6] Access costs depend on the technology of

[6]This cost function determines how costly it is for an individual to access information from a storage device or from another individual. The *average* access cost would be the average cost paid by all individuals who wish to acquire the knowledge. More relevant for most useful questions is the *marginal* access cost, that is, the *minimum* cost for an individual who does not yet have this information. A moment reflection will make clear why this is so: it is very expensive for the average member of a society to have access to the Schrödinger wave equations, yet it is "accessible" for advanced students of quantum mechanics at low cost. If the rest of society "needs" to know something it will clearly go to someone for whom this cost is as low as possible to find out. Such people would then be defined as experts, and much of the way knowledge has been used has relied on such experts. The cost of finding these experts and retrieving knowledge from them thus determines marginal access costs. Equally important, as we shall see, is the technology that provides access to storage devices.

access, the trustworthiness of the sources, as well as on the total size of S; the larger it is, the more specialization and division of knowledge is required. Experts and special sources dispensing useful information will emerge providing access. Information Technology is exactly about that. The much heralded IT revolution of our own age is not just about the fact that we *know* more (and different) things, but that the flows of information in and out of agents' minds are much more rapid. The continuous interchange of useful knowledge between the minds of agents and between those of other agents and storage devices has been greatly speeded up and become enormously cheaper in the past ten years. Access costs also depend on the *culture* of knowledge: if those who possess it regard it as a source of wealth, power, or privilege, they will tend to guard it more jealously. Secrecy and exclusionary practices are, of course, artificial ways to increase access costs. To be sure, language, notation, and jargon were also barriers to access (as they are today) but "popularized" versions of scientific books became necessary if scientists were to reach their paying audiences and patrons.

For the historian, the dynamic questions about S are the most interesting. An evolutionary approach can help us clarify our thinking about it, although analogies with biology and genetics have to be pursued with caution (Mokyr, 1998a, 1998b). Much like DNA, useful knowledge does not exist by itself, it has to be "carried" by people or in storage devices. Unlike DNA, however, carriers can acquire and shed knowledge so that the selection process is quite different. Clearly this raises question of how it is transmitted over time, and whether it can actually shrink as well as expand. All carriers have finite lives and thus need to reproduce themselves in some fashion. The existence of non-living carriers does expedite this transmission, but it is also clear that some crucial components cannot be codified or stored in devices that require codification. This "tacit" knowledge cannot be stored and therefore dies with its live carrier. In principle there is nothing to stop knowledge from being lost altogether or becoming so expensive to access that for all practical purposes it might as well be. Much of the likelihood of knowledge being transmitted depends on the social organization of knowledge, storage technology, and who controls access to it. If useful knowledge is controlled by an Imperial bureaucracy, as was the case in China, or a small aristocratic elite, as was the case in classical civilization, much of it can be lost or made inaccessible. These social conditions also determine how likely it is that S will expand, that is, that new discoveries and knowledge will be added.

In addition to useful knowledge about the natural world, there is a second form of knowledge which I call techniques. Techniques are essentially sets of instructions or recipes on how to manipulate nature. These instructions, like all knowledge, either reside in people's brains or in storage devices. It consists of designs and instructions on how to adapt means to a well defined end, much like a piece of software or a cookbook recipe. They are usually the end-product of some knowledge in S so they have an *epistemic base* in S. I will refer to this set as 8. If S is *episteme*, 8 is *techne*. Elements of 8 consist of “do loops” replete with “if-then” statements instructing one on how to carry out certain activities that broadly constitute what we call “production.” They all can be taught, imitated, and improved upon. A “how to” manual is a codified set of techniques. Not all techniques are explicit, codified, or even verbalized. Thus riding bicycles or playing a musical instrument consist of neuro-muscular movements that cannot be made entirely explicit.[7] Others consist of “tacit” knowledge that could be made explicit but never is. Much like elements of S, the elements of 8 require carriers to be expressed (that is, used) and transmitted over time and across space. Each society has some metaset of all techniques feasible to it, a monstrous compilation of blueprints and instruction “manuals” that describe what this society *can* do. These are often hard to pin down.[8] All the same, they must have existed. From that set, economic decision makers be they households, small producers, or large corporations, select techniques. This choice is the technological analogue of natural selection and since Nelson and Winter (1982) first enunciated it in 1982, it has remained the best way to describe and analyze technological change (Nelson, 1995).

Naturally, only a small subset of 8 is in use at each point of time. How society “selects” these techniques and rejects others is an important question, but not one I will address here (see Mokyr, 1998a). Techniques, too, need to be passed on from generation to generation because of wear and tear to their carriers and can be taught without necessarily including the entire body of S that serves as their base: a plumber can be trained to fix leaking pipes without burdening him with the hydraulics and material science underlying his skill -- though in general the more of the underlying knowledge passed on, the better the skills. To be sure, an invention in plumbing *could* be made through pure luck or inspiration by someone totally ignorant of these areas, but the probability of this happening quickly declines not only with the complexity of the problem but also with the number of previous serendipitous inventions.

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[7]Many techniques have elements and refinements that can only be stored in people’s minds and transmitted, if at all, by personal contact. Some of them are “knacks” that are uncodifiable and defy any formalization, and if valuable enough, yield large rents to their carrier. Thus the skills of basketball- or violin-playing can be codified and taught, but the techniques applied by Michael Jordan or Itzhak Perlman clearly are not wholly transmissible.

[8]Hall (1978, p. 96) points out that the historian finds it very difficult to identify 8 from early records, because in the past shipwrights, toolmakers, and so on left few records of their “instructions” and inferring these from the end-products can be misleading.

Is the distinction between S and 8 meaningful? Both reflect some form of knowledge and thus are subject to the same kind of difficulties that economics of knowledge and technology encounters. But the knowledge set is partitioned by *kinds* of knowledge. Michael Polanyi (1962, p. 175) points out that the difference boils down to observing that S can be “right or wrong” whereas “action can only be successful or unsuccessful.” He also notes that the distinction is recognized by patent law which will patent inventions (additions to 8) but not discoveries (additions to S). Yet Polanyi fails to recognize the important historical implications of the two kinds of knowledge and maintains that “up to [1846] natural science had made no major contribution to technology. The Industrial Revolution had been achieved without scientific aid” (p. 182). Yet the implicit definition he uses for S implies a much larger entity than formal science.[9] The distinction between S and 8 parallels the distinction made famous half a century ago by Gilbert Ryle (1949), who distinguished between knowledge “how” and knowledge “what.” Ryle rejected the notion that one can meaningfully distinguish *within a single individual* knowledge of a set of parameters about a problem and an environment from a set of instructions derived from this knowledge that directs an individual to take a certain action. Yet what may not be true for an individual is true for society as a whole: for a technique to exist, it normally has an epistemic base in S. In other words, somebody needs to know enough about a natural principle or phenomenon on which a technique is based to make it possible.[10] How much “enough” is, depends on the complexity of the technique and many other factors. It is not necessary, moreover, that the same person carrying out the technique have access to this knowledge: I typed these lines on a computer even though I have only rudimentary knowledge of the physical and mathematical rules that make my computer work. But at some time in the past, somewhere, somebody had this knowledge; the probability that a laptop computer would be made by a group of people with no knowledge of computer science, advanced electronics, materials science, and whatever else is involved is nil. Layton (1974, p. 40) remarks that “'knowing' and 'doing' reflect the fundamentally different goals of communities of science and technology.” But most of what is in S has nothing to do with understanding the universe but with mundane, prosaic properties of materials, motion, temperature, mechanisms, and living beings: simple natural regularities that imply certain actions

[9]In addition to “pure science”, he includes an intermediate set of enquiries that are “systematic technology” and “technically justified science.” Yet he must mean even less formal elements when he points out that “technology always involves the application of some empirical knowledge... our contriving always makes use of some anterior observing”(Polanyi, 1962, p. 174).

[10]Strictly speaking, even if S is the null set, some elements in 8 *could* exist. A beaver’s technique of building dams or bees’ ability to construct hives are techniques that have no demonstrable basis in anything we could define as useful knowledge.

and rule out others. It should also be kept in mind that S contains such elements as "technique 8_i exists and works satisfactorily" and hence the diffusion of techniques in 8 depends on the characteristics of S. Different elements in 8 may be involved in constructing artefacts and using them, writing down the instructions and interpreting them, and so on. Useful knowledge is a social good, and as long as it exists *somewhere* and others have access to it, it can result in improved techniques, that is, lead to technological progress.[11]

The set S maps into 8 and thus imposes a constraint on it. Certain societies, including our own, do not have access to some techniques because they lack a base in S. Medieval Europe could not design a technique describing the ocean route to Australia or how to produce antibiotics against the Black Death. Our own societies have been unable to tame nuclear fusion and make effective anti-virus agents because we do not know enough about high-energy physics and virology. Nonetheless, we cannot be sure that such knowledge will never exist; all that matters is that *we* do not have it. I have argued elsewhere that the relationship between S and 8 is in some ways akin to the relationship between genotype and phenotype in evolutionary biology in that not every gene ends up coding for a protein, but for any phenotype to emerge, some basis for it has to exist in the genome. Of course, the existence of some piece of knowledge does not guarantee that any mapping will occur. Hellenistic civilization created Ptolemaic astronomy but never used it, apparently, for navigational purposes. The Chinese under the Song had excellent knowledge of clockmaking but never used it for anything but ornamental devices, nor did their understanding of optics translate into the making of binoculars or eyeglasses. What matters, clearly, is the incentive and penalty structure for people who suggest new techniques. New techniques can emerge from pure novelty much like mutations, or from recombining existing elements in S in novel ways. On the way they encounter all kinds of technological and political resistance, and only the smallest fraction of novelties ever find their way to usage.

There are thus interesting parallels and important differences between technological and biological evolution.[12] Yet it could be misleading to think of the mapping from S to 8 as equivalent to the mapping from genotype to phenotype. In technology, unlike in biology, the epistemic base on which a technique rests is not

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[11]The distinction I am making here is somewhat different from the one that formed the basis of a debate between Layton (1974) and Hall (1978) about the validity of a distinction between "knowledge" and "knowledge how."

[12]For more details on this line of thinking, see Mokyr (1998a, 1998b).

wholly determinate. Moreover, unlike what happens in biology, 8 can produce a feedback into S. As we shall see, this feedback is of pivotal historical importance.

The mapping function remains one of the more elusive historical phenomena and is the key to explanations of "invention" and "technological creativity." What has not been sufficiently stressed, however, is that changes in the size and internal structure of S can themselves affect the chances that it will be mapped and the nature of the techniques that will emerge. Above all, the boundaries of S at any moment limit what *can* be mapped.

As noted, the epistemic base of techniques can be narrow or wide. The narrower the base in S of a particular technique, the less likely it is to keep growing and expanding after its first emergence. In the absence of a good understanding of why and how a technique operates, further improvements ran quickly into diminishing returns. In the limiting case, the base of a particular technique is so narrow that *all* that is known (and is thus contained in S) is the trivial element that "technique i works." These techniques, which might be called "singleton techniques" (since their domain is a singleton), usually emerged as the result of serendipitous discoveries. Much technological progress before the Industrial Revolution was of that nature. While new techniques appeared, they rarely if ever led to continued and sustained further improvements and attain the cumulative momentum that provides most of the economic benefits of innovation. While at times they had enormous practical significance, they were usually dead ends. Such techniques are also less flexible and adaptable to changing circumstances, a problem that is particularly acute in medicine (Mokyr, 1998).[13] Thus Jenner's 1796 discovery of the vaccination process, one of the most successful singleton techniques in history, led to no further vaccinations until the triumph of the germ theory, and smallpox flare-ups due to ignorance and improper usage were common till the end of the nineteenth century. The correct use of fertilizer in agriculture in ancient times improved but slowly until the development of organic chemistry by von Liebig and his followers and the systematic experimentation of John Benet Lawes at Rothamsted after 1840. The more complex a technology, the less likely that a singleton technique will be discovered. All the same, pharmaceutical research still has room for serendipity and contains an element of "try every bottle on the shelf." When a compound is discovered that works for a particular purpose, the fine details of its *modus*

[13]Hall (1978, p. 97) points out that a shipwright who knows "how" to build a ship without having any knowledge of the underlying rules would not be able to build a whole series of different ships.

operandi often emerge much later.[14] Alternative medicine, to pick another example, is full of narrow-based or singleton techniques that have little basis in S.[15] Techniques that have narrow or negligible bases in S tend also to be "untight" and their inventors encounter more difficulty persuading the public to use them if only because something might be more believable if it is known not only that it seems to work but also *why*. This tightness depends on other factors as well: if the technique is demonstrably superior, its base in S may have little effect on its acceptability (as was surely the case with Jenner).[16]

The dynamics of information differ in crucial ways from that of DNA: there is a feedback loop going back from 8 to S in which knowledge about "how" feeds back into knowledge about "what." The simplest case occurs when a technique is discovered serendipitously and the fact that it works is translated into the realm of S. But changes in techniques also open up new scientific questions and technical developments in instruments and laboratory methods make new research possible. Positive feedback from S and 8 and back can lead to virtuous cycles much more powerful than can be explained by technological progress or scientific progress separately. The self-sustained nature of the process occurs because the two types of knowledge are complementary in the technical sense that a growth in one increases the marginal product of the other (Milgrom, Qian, and Roberts, 1991). If there is sufficient complementarity between an upstream process (S) and a downstream process (8) in the system, persistent, self-reinforcing economic change can occur even without increasing returns. It could also be thought that there are feedback mechanisms from 8 onto itself, in that new technology leads directly to further new technology. Historically, of course, this was precisely the nature of technological change, but a proper definition of S (which includes the "master catalog" of all elements in 8) would keep the formal mechanics straight.

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[14] As *The Economist* putsit in its Millennium Special Issue, before Djerassi drugs were developed it in a "suck it and see" fashion: either their mode of action remained unknown, or it was elucidated after their discovery. *The Economist,* Jan 1, 2000, p. 102.

[15] Thus magnetic pain therapy, in which magnets are used to relieve pain -- by now a multibillion industry in the United States -- is agnostic on its base in S; nobody who believes that this technique is effective (still a small minority) seems to have any serious idea or care very much about *how* it is supposed to work.

[16] Yet clearly this is not invariably the case. An example is the conquest of scurvy. The importance of fresh fruit in the prevention of scurvy had been realized even before James Lind published his *Treatise on Scurvy* in 1746. The Dutch East India Company kept citrus trees on the Cape of Good Hope in the middle of the seventeenth century, yet despite the obvious effectiveness of the remedy, the idea obviously did not catch on and the idea "kept on being rediscovered and lost" (Porter, 1995, p. 228). In any event, apart from the fact that there was an apparent connection between the consumption of fresh fruit and vegetable and the occurrence of scurvy, nothing was added to S until a century and a half later.

One of the interesting characteristics of these evolutionary models of knowledge is that they imply that the tightness of S and 8 are mutually reinforcing. Knowledge in S will become tighter if it maps into techniques that actually can be shown to work. Thus once biologists discovered that insects could be the vectors of pathogenic microparasites, insect-fighting techniques gained wide acceptance. The success of these techniques in eradicating yellow fever and malaria was the best confirmation of the hypotheses about the transmission mechanisms of the disease and helped gain them wide support. Another example is the relationship between aeronautics and the techniques of building machines that would actually fly.[17] To put it crudely, the way we are persuaded that science is true is that its recommendations work visibly: chemistry works – it makes nylon tights and polyethylene sheets (Cohen and Stewart, 1994, p. 54). Strictly speaking, this is not a correct inference, because a functional technique could be mapped from knowledge that turns out to be false. At the same time, techniques may be "selected" because they are implied by a set of knowledge that is gaining acceptance.[18] The chronological order of this mutual reinforcement between S and 8 differs from case to case, but at least since the middle of the nineteenth century there is a gradual if incomplete shift toward a priority of S. That is to say, in the twentieth century more and more techniques require some prior scientific breakthrough before they become feasible although almost invariably the technique feeds back into the science.

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[17]The fundamentals were laid out early by George Cayley in the early nineteenth century. Much of the knowledge in this branch of engineering was experimental rather than theoretical, namely, attempts to tabulate coefficients of lift and drag for each wing shape at each angle. The Wright brothers relied on the published work (especially of Otto Lilienthal) at the time to work out their own formulas, but they also ended up working closely with the leading aeronautical engineer of the time, Octave Chanute, who supplied them with advice right up to Kitty Hawk (Crouch, 1989). It is clear, however, that the Wright brothers were avid consumers of engineering science and that their greatness lies precisely in the mapping function.

[18]For an example of the give and take between S and 8 in the case of household technology and bacteriology in late nineteenth century, see Mokyr and Stein (1997) and Mokyr (1997, 1998d).

Knowledge, Science, and Technology during the Industrial Revolution

The Industrial Revolution was not the beginning of economic growth. There is by now considerable evidence that on the eve of the Industrial Revolution Britain and other parts of Western Europe had gone through long periods of economic growth, perhaps not as sustained and rapid as modern economic growth, but growth all the same (Mokyr, 1998c, pp. 34-36 and sources cited there). It remains to be seen how much of this growth can be attributed to increases in technological knowledge about production and how much to other factors, such as gains from trade or more efficient allocations. Much of the analysis of growth in history, of course, does not lend itself to such neat decompositions: the geographical discoveries after 1450 and improvements in shipping and navigational technology were in and of themselves a pure growth in S, mapping into improved techniques, but they led to increased trade as well. The Industrial Revolution, however, constitutes a stage in which the weight of the knowledge-induced component of economic growth experienced a marked increase. It did not start from zero, nor did it go to unity. All the same, the period 1760-1815 was one in which continuous political disruptions must have reduced the importance of "Smithian growth." Britain was able to sustain a rapidly rising population without a sharp decline in income, which may be regarded as a signal for a new "type" of growth.

It has become a consensus view that economic growth as properly defined was very slow during the Industrial Revolution, and that living standards barely nudged upward until the mid 1840s (Mokyr, 1998c). There have even been some voices calling for abandoning the term altogether. Yet it is by now recognized that there are considerable time lags in the adoption and macroeconomic effects of major technological breakthroughs and so-called General Purpose Technologies and that growth traditionally measured even during the difficult 1760-1815 years was, in fact, respectable once we take into account the negative political and demographic shocks of the period. In the longer run, the macroeconomic effects of the technological breakthroughs that constituted the Industrial Revolution have not seriously been questioned. The growth of *scientific* knowledge was part of this knowledge, but a relatively small part. Most practical useful knowledge in the eighteenth century was uncodified, unsystematic, and informal, passed on from master to apprentice or horizontally between agents. Yet formal and informal knowledge were strict complements in the development of new techniques, and the technology of knowledge transmission itself played a major role.[19]

The true question of the Industrial Revolution is not why it "took place" at all but why it was sustained beyond, say, 1820. There had been earlier clusters of macroinventions, most notably in the fifteenth century with the emergence of movable type, the casting of iron, and advances in shipping and navigation technology. Yet in the earlier cases these mini-industrial revolutions had always petered out before their effects could launch the economies into sustainable economic growth. Before the Industrial Revolution, the economy was characterized by negative feedback; each episode of growth in the end ran into some obstruction or resistance of some sort that put an end to it.[20] The best-known of these negative feedbacks mechanisms are Malthusian traps, a prime example of negative feedback, and technological resistance in which entrenched interests were able to stop technological progress using non-market mechanisms (Mokyr, 1994a, 1994b, 1998e). What was different in the eighteenth century is that the Scientific Revolution and the Enlightenment changed the structure of S to the point where useful knowledge could increase abruptly by continuously feeding on itself whereas previously it always was suppressed by economic and social factors.[21] Negative feedback was thus replaced by positive feedback, which eventually became so powerful that it became self-sustaining. Such positive feedback effects between S and 8 resulted in a self-reinforcing spiral of knowledge augmentation that was impossible in earlier days of engineering without mechanics, iron-

[19]Margaret Jacob (1997), whose work has inspired much of what is to follow, summarizes the developments in eighteenth century Europe as follows: "Knowledge has consequences. It can empower; if absent, it can impoverish and circumstances can be harder to understand or control" (p. 132). Yet her statement that "people cannot do that which they cannot understand, and mechanization required a particular understanding of nature that came out of the sources of scientific knowledge" (p. 131) goes too far. Depending on what one means by "understand," it is obvious that people *can* do things they do not understand, such as build machines and design techniques on the basis of principles and laws that are poorly or misunderstood at the time.

[20]An early use of the idea of such feedbacks is found in Needham's description of the dynamics of Imperial China, which he describes as a "civilization that had held a steady course through every weather, as if equipped with an automatic pilot, a set of feedback mechanisms, restoring the status quo [even] after fundamental inventions and discoveries" Needham, 1969, pp. 119-20. Needham may overstate the degree of technological instability in pre-1750 Europe, but his intuition about the difference between the two societies being in the dynamic conditions of stability is sound.

[21]An explanation of this phenomenon has been proposed recently by David (1998). He envisages the community of "scientists" to consist of local networks or "invisible colleges" in the business of communicating with each other. Such transmission between connected units can be modelled using percolation models in which information is diffused through a network with a certain level of connectivity. David notes that these models imply that there is a minimum level of persistently communicative behavior that a network must maintain for knowledge to diffuse through and that once this level is achieved the system becomes self-sustaining.

making without metallurgy, farming without organic chemistry, and medical practice without microbiology.[22] "Growth" in S meant not only an increase in the *size* of S (through discovery) but also in its *density* (through diffusion). All in all, the widening of the epistemic base of technology meant that the techniques that came into use after 1750 relied on a broader and broader base in S. This made a gradual stream of improvements and microinventions possible. In short, the Industrial Revolution should be understood in the context of changes in useful knowledge and its applications.

How much of the changes in S in Britain before and during the Industrial Revolution could be attributed to what we would call today "science?" The notion that Britain was the first to undergo an Industrial Revolution because somehow British technological success was due to Britain's having more "advanced" science is unsupportable. The premise itself is in dispute (Kuhn, 1977, p. 43), but even if it were true, the consensus is that techniques developed during the British Industrial Revolution owed little directly to "scientific knowledge" as we would define it today. Unlike the technologies that developed in Europe and the United States in the second half of the nineteenth century, science, by conventional wisdom, had little direct guidance to offer to the Industrial Revolution (Hall, 1974, p. 151). Gillispie (1957) points out that the majority of scientific endeavors of the time concerned subjects of limited technological use: astronomy, botany, crystallography and early exploration of magnetism, refraction of light, and combustion. Eventually many of those discoveries found economic applications, but these took place, with few exceptions, after 1830.

If science played a role in the Industrial Revolution, it was first and foremost through the incidental spillovers from the scientific endeavor on the properties of S. These spillovers affected the way in which *new* knowledge was generated, but equally important they affected the technology and culture of access to information. We may distinguish among three closely interrelated phenomena: scientific method, scientific mentality, and scientific culture. The penetration of scientific *method* into technological research meant accurate measurement, controlled experiment, and an insistence on reproducibility. William Eamon (1990), and more recently Paul David (1997) have pointed to the Scientific Revolution of the seventeenth century as the period in which "open science" emerged, when knowledge about the natural world became increasingly

[22] As Cohen and Stewart (1994, pp. 420-21) point out, because S and 8 have a different "geography," their attractors do not match up nicely and "the feedback between the spaces has a creative effect... the interactions create a new, combined geography that in no sensible way can be thought of as a mixture of the two separate geographies."

non-proprietary and scientific advances and discoveries were freely shared with the public at large. Thus scientific knowledge became a public good, communicated freely rather than confined to a secretive exclusive few as had been the custom in medieval Europe. This sharing of knowledge within “open science” required systematic reporting of methods and materials using a common vocabulary and consensus standards. Scientific “method” here also should be taken to include the changes in the rhetorical conventions that emerged in the seventeenth century, during which persuasive weight continued to shift away from pure “authority” towards empirics, but which also increasingly set the rules by which empirical knowledge was to be tested so that useful knowledge could be not only accessed but trusted.[23] Margaret Jacob (1997, p. 115) has indeed argued that by 1750 British engineers and entrepreneurs had a “shared technical vocabulary” that could “objectify the physical world” and that this communication changed the Western world forever. These shared languages and vocabularies are precisely the stuff of which reduced access costs are made of.

Even more important, perhaps, was scientific *mentality*, which imbued engineers and inventors with a faith in the orderliness, rationality, and predictability of natural phenomena -- even if the actual laws underlying chemistry and physics were not fully understood (Parker, 1984, pp. 27-28). Because technology at base involves the manipulation of nature and the physical environment, the metaphysical assumptions under which people engaged in production operate are ultimately of crucial importance. The growing belief in the rationality of nature and the existence of knowable natural laws that govern the universe, the archetypical enlightenment belief, led to a growing use of mathematics in pure science as well as in engineering and technology. In this new mode, more and more people rebelled against the idea that knowledge of nature was “forbidden” or better kept secret (Eamon, 1990). Scientific mentality also implied an open mind, a willingness to abandon conventional doctrine when confronted with new evidence, and a growing persuasion that no natural phenomenon was beyond systematic investigation and that deductive hypotheses could not be held to be true until tested. Yet, as Heilbron (1990) and his colleagues have argued, in the second half of the eighteenth century “truth” became less a concern than an “instrumentalist” approach to scientific issues, in which quantifying physicists and chemists surrendered claims to “absolute truth” for

[23]Shapin (1994) 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. While the approach to science was ostensibly based on a “question authority” principle [the Royal Academy's motto was *nullius in verba* -- on no one's word --] in fact no system of useful or any kind of knowledge can exist without some mechanism that generates trust. The apparent scepticism with which scientists treated the knowledge created by others increased the trust that others had in the findings, since outsiders could then assume -- as is still true today -- that these findings had been scrutinized and checked by other “experts.”

the sake of a more pragmatic approach and gained ease of calculation and application of the regularities and phenomena discovered.

Finally, scientific *culture*, the culmination of Baconian ideology, placed applied science at the service of commercial and manufacturing interests (Jacob, 1997). Science in the seventeenth century became increasingly permeated by the Baconian motive of material progress and constant improvement, attained by the accumulation of knowledge.[24] Scientific culture led to the gradual emergence of engineering science and the continuous accumulation of orderly quantitative knowledge about potentially useful natural phenomena in "all matters mineral, animal, and vegetable."[25] Although such relations are impossible to quantify, it stands to reason that in that regard science laid the intellectual foundations of the Industrial Revolution by providing the tacit and implicit assumptions on which technological creativity depended.

Returning to the framework laid out earlier, these developments changed the internal structure of S during the eighteenth century and early nineteenth century. They created "a community" of knowledge, within which much of the knowledge resided. It matters less what one individual knows than what the community "knows" -- that is, the size of S. Yet the significance of communal knowledge matters for economic history only if it can be accessed, believed, and used. Useful knowledge, as Shapin points out, is always communal. No individual can know everything. Western societies experienced both an increase in the size of S and an ever-growing ability to map this useful knowledge into new and improved techniques, as access costs declined and new principles of authority, expertise, and verifiability were set up.

[24]Robert K. Merton (1970 [1938], pp. ix, 87) asked rhetorically how "a cultural emphasis upon social utility as a prime, let alone an exclusive criterion for scientific work affects the rate and direction of advance in science" and noted that "science was to be fostered and nurtured as leading to the improvement of man's lot by facilitating technological invention." He might have added that non-epistemic goals for useful knowledge and science, that is to say, goals that transcend knowledge for its own sake and look for some application, affected not only the rate of growth of the knowledge set but even more the chances that existing knowledge will be translated into techniques that actually increase economic capabilities and welfare.

[25]The paradigmatic figure in the growth of the subset of S we now think of as "engineering" knowledge was John Smeaton (1724-1792). Smeaton's approach was pragmatic and empirical, although he was well versed in theoretical work. He limited himself to ask questions about "how much" and "under which conditions" without bothering too much about the "why." Yet his approach presupposed an orderliness and regularity in nature exemplifying the scientific mentality. Vincenti (1990, pp. 138-140) and Cardwell (1994, p. 195) attribute to him the development of the method of parameter variation through experimentation, which is a systematic way of gradual improvements in 8. It establishes regularities in the relationships between relevant variables and then extrapolates outside the known relations to establish optimal performance. At the same time, Smeaton possessed a great deal of the non-scientific component of useful knowledge: in the little workshop he used as a teenager, he taught himself to work in metals, wood and ivory and could handle tools with the expertise of a regular blacksmith or joiner (Smiles, 1891). It may well be, as Cardwell notes, that this type of progress did not lead to new macroinventions, but the essence of progress is the interplay between "door-opening" and "gap-filling" inventions. Setting up this systematic component in the mapping from S to 8, in addition to his own wide-ranging contributions to engineering, stamp Smeaton without question as one of the "Vital Few" of the Industrial Revolution.

Some developments in the cost of access are well known and documented. The Royal Society, of course, was the very embodiment of the ideal of the free dissemination of useful knowledge.[26] In eighteenth and early nineteenth century Britain, popular lectures on scientific and technical subjects by recognized experts drew eager audiences. Some of these were given at scientific society meeting places, such as the famous Birmingham Lunar Society whereas others were given in less famous societies in provincial towns such as Hull, Bradford, and Liverpool. Still others were freelance and ad hoc, given in coffeehouses and masonic lodges. Audiences breathlessly watched experimental demonstrations illustrating the application of scientific principles to pumps, pulleys, and pendulums (Inkster, 1980). Yet, as Robert Schofield (1972) has argued, the formal meetings were secondary to the networking and informal exchange of technical information among members. Scientific culture reinforced the entrepreneurial interests of science's audience by demonstrating how applied mechanics could save costs and enhance efficiency and thus profits. Outside England, formal technical education played a larger role in fulfilling these functions. In France, artillery schools opened in the 1720s; in the late 1740s the *École des Ponts et Chausées* and the *École du génie* for military officers were opened, to be followed famously by the *Polytechnique* in 1794. Other countries on the Continent followed suit, with mining schools founded in Saxony and Hungary, among others. England, where the public sector rarely intervened in such matters, lagged behind in formal education, but its system of public lectures, informal scientific societies, and technical apprenticeship sufficed -- for the time being. Yet what was there in natural knowledge that the mechanics and engineers felt they needed?

Despite its apparent shortcomings, eighteenth century scientific knowledge did provide implicit theoretical underpinnings to what empirically minded technicians did, even if the epistemic base was still narrow compared to what it would become later. Without certain elements in S, many of the new techniques would not have come into existence at all or not worked as well. Thus the steam engine depended both on the understanding of atmospheric pressure, discovered by Continental scientists such as Evangelista Torricelli and Otto von Guericke, and the early seventeenth century notion that steam was evaporated water and its

[26]The idea of reducing access costs encountered the kind of problem that is typical in "markets" for technological knowledge, namely how best to secure some form of appropriability for a public good. The Royal Society's project on the history and description of trades (i.e. manufacturing) ran into the resistance of craftsmen reluctant to reveal their trade secrets (Eamon, 1990, p. 355).

condensation created a vacuum.[27] This discovery led to the idea that this pressure could be used for moving a piston in a cylinder, which could then be made to do work. The proto-idea of an engine filtered down to Newcomen despite the fact that his world was the local blacksmith's rather than the cosmopolitan academic scientist's. Improvements in mathematics, especially the calculus invented by Leibniz and Newton, became increasingly important to improvements in the design and perfection of certain types of machinery although in many areas its importance did not become apparent until much later. The advances in water power in the eighteenth century depended increasingly on a scientific base of hydraulic theory and experimentation despite a number of errors, disputes, and confusions (Reynolds, 1983).[28] The importance of water power in the Industrial Revolution is still not given its due recognition because steam was more spectacular and in some sense more revolutionary.[29] The technique of chlorine bleaching depended on the prior discovery of chlorine by the Swedish chemist Carl Wilhelm Scheele in 1774. Phlogiston theory, the ruling physical paradigm of the eighteenth century, was eventually rejected in favor of the new chemistry of Lavoisier but some of its insights (e.g., the Swede Tobern Bergman's contributions to metallurgy) were valuable, even if their scientific basis seems flawed and their terminology quaint to modern readers. Cardwell (1972, pp. 41-43) has shown that the idea of a measurable quantity of “work” or “energy” derived directly from Galileo's work on mechanics and played a major role in the theories and lectures of engineers such as Desaguliers. Harrison’s great marine chronometer was only conceivable in the context in which S already contained the observation

[27]Usher (1954, p. 342) attributes this finding to Solomon De Caus, a French engineer and architect in a 1615 book. Uncharacteristically, Usher is inaccurate here: in 1601, Giambattista Della Porta already described a device based on the same idea, and both were apparently inspired by the appearance in 1575 of a translation of Hero of Alexandria's *Pneumatics* which, while not grasping either the notion of an atmospheric engine nor that of a condensation-induced vacuum, focused the attention on steam as a controllable substance. It is hard to imagine anyone reading Hero without realizing that steam was evaporated water and that upon condensation “the vapor returns to its original condition.”

[28]The input of formal mathematics into technical engineering problems was most remarkable in hydraulics and the design of better water wheels in the eighteenth century. Theoreticians such as the Eulers and Charles Borda made major contributions towards the understanding of the relative efficiency of various designs. It should be added however that experimental work remained central here and at times had to set the theorists straight. See especially Reynolds, (1983). Calculus also found its way into mechanical issues in construction such as the theory of beams, especially Charles Coulomb in his celebrated 1773 paper applying calculus to “Statical Problems with Relevance to Architecture.”

[29]John Smeaton was well-versed in the theoretical writings of French hydraulic scientists such as Antoine de Parcieux. In the 1750s, Smeaton carried out experiments showing that the efficiency of overshot wheels tended to be around 2/3, while that of undershot wheels was about 1/3. In 1759 he announced his results firmly establishing the superiority of the gravity wheel. At that point, Smeaton realized the vast potentialities of the breast wheel: it was a gravity wheel, but one that could be constructed in most sites previously suitable only for undershot wheels. Once fitted with the tightly fitting casing, it combined the advantages of the gravity and the impulse wheels. The breast wheel turned out to be one of the most useful and effective improvements to energy generation of the time.

that longitude could be determined by comparing local time with time at some fixed point. Often, of course, bogus science produced bogus results, as in Jethro Tull's insistence that air was the best fertilizer and the amazingly eccentric theories still rampant in late eighteenth century medicine.[30]

In the “development” stage of basic inventions – in which engineers and technicians on the shopfloor improved, modified, and debugged the revolutionary insights of inventors such as Arkwright, Cartwright, Trevithick, and Roberts to turn them into successful business propositions – pure science played only a modest role. The mechanical inventions that constituted the Industrial Revolution involved little formal science, yet they still required a great deal of the pragmatic and informal knowledge of how certain materials respond to physical stimuli and heat, how the selective breeding of animals can be accomplished, how motion can be transmitted through pulleys and shafts, how and where to lubricate moving parts to reduce friction, and similar components of S. What is clear is that Britain was a society that provided both the incentives and the opportunities to apply useful knowledge to technology.

An example of how such partial knowledge could lead to a new technique was the much hailed Cort puddling and rolling technique.[31] The technique depended a great deal on prior knowledge about natural phenomena, even if the epistemic basis of the technique in terms of the physics and chemistry of metallurgy was still in the future. Cort realized full-well the importance of turning pig iron into wrought or bar iron by removing what contemporaries thought of as “plumbago” [a term taken from phlogiston theory and equivalent to a substance we would call today carbon]. The problem was to generate enough heat to keep the molten iron liquid and to prevent it from crystallizing before all the carbon had been removed. Cort knew that reverberating furnaces using coke generated higher temperatures. Cort also realized that by rolling the hot metal using grooved rollers, its composition would be much more homogenous. How and why he mapped this prior knowledge into his famous invention is not exactly known, but the fact that so many other

[30]A Scottish physician by the name of John Brown (1735-88) revolutionized the medicine of his age with Brownianism, a system that postulated that all diseases were the result of over- or under-excitement of the neuromuscular system by the environment. Brown was no enthusiast for bleeding, and treated all his patients instead with mixtures of opium, alcohol, and highly seasoned foods. His popularity was understandably international: Benjamin Rush brought his system to America, and in 1802 his controversial views elicited a riot among medical students in Göttingen, requiring troops to quell it. Brown was asserted to have killed more people than the French Revolution and the Napoleonic Wars combined (cited by McGrew, 1985, p. 36).

[31]Hall (1978, p. 101) points to the puddling process as an example of a technique in which “useful knowledge” did not matter: a man either knows how to do it or he does not. Clearly this refers to the person actually carrying out the technique, not the technique itself.

ironmasters were following similar tracks indicates that they were all drawing from a common pool.[32] All the same, it should be kept in mind that in coal and iron above all, craft-based tacit skills were of unusual importance in the finer details of the jobs, and that codifiable knowledge more than anywhere else would be insufficient in these industries unless accompanied by these informal skills (Harris, 1976).

Another example, not normally part of the history of the Industrial Revolution, is that most paradigmatic of all macroinventions, ballooning, which for the first time in history broke the tyranny of gravity. Speculation over how the idea first emerged is widespread, but Bagley's (1990, p. 609) verdict that "there is no apparent reason why this technology could not have appeared centuries earlier" is contradicted by the fact that British scientists had only discovered gases lighter than air -- specifically "inflammable air" (hydrogen) isolated by Cavendish -- and the knowledge that hot air expands and thus becomes lighter, in 1766. This knowledge was communicated to Joseph Montgolfier by his cousin, a medical student at Montpelier. Needless to say, the scientific basis of ballooning was not yet altogether clear, and contemporaries did not see for instance, that there was a fundamental difference between physically (hot air) and chemically (hydrogen) filled balloons (Gillispie, 1983, p. 16). But *some* knowledge was necessary, and the timing seems better explained this way.

To summarize, then, the changes in technological knowledge in the century after 1750 involved three different types of processes. First, there were pure additions to S that occurred as part of an autonomous system of discovery about nature unrelated to economic needs and conditions. The great discoveries of Cavendish and Lavoisier establishing modern chemistry were clearly in this category. Such expansions in useful knowledge led to new mappings and eventually became one of the driving forces behind technological advances. Second, there were changes in some of the properties of S and 8, which became denser (more people shared the knowledge) and more accessible (better organized and easier to communicate). These changes yielded new mappings into 8, that is inventions, drawing both on the new and a pre-existing pool of knowledge. At first glance it may be hard to see, for instance, what there was in the original spinning

[32]Reverberatory furnaces had been used in glassmaking and were first applied to iron by the Cranage brothers in Coalbrookdale. Puddling had been experimented with by the Cranage brothers as well, as well as by Richard Jesson and Peter Onions (who both took out similar patents two years before Cort's success). Grooved rolling had been pioneered by the great Swedish engineer Christopher Polhem. None of those attempts seems to have had much success: recombining obviously must be done in some specific way and not others.

jennies that could not have been conceived a century before.[33] Yet once such techniques are discovered, the knowledge that they are possible becomes part of S, and subsequent inventors can then draw upon it. Crompton's mule was a standard example of recombining two existing techniques into a novel one. Explaining the exact timing of such mappings is impossible, but the changing structure of S in terms of density and access costs was of central importance. In other words, changes in the overall size of S (what was known) may have been less important in the Industrial Revolution than the *access to* that knowledge. Moreover, the process was highly sensitive to outside stimuli and incentives. The social and institutional environment has always been credited with a central role in economic history. All I would argue is that the set-up proposed here sheds some light on *how* this mechanism worked.[34] In that respect the evolution of technology again resembles biological evolution: changes in the environment (including changes in the availability of complements and substitutes) may trigger the activation of existing knowledge or select those techniques that happen to "express" information adapted to a new environment.

Third, there was feedback from techniques to knowledge. A great number of major and minor scientific revolutions were driven not just by conceptual innovation but by new tools and techniques.[35] Famous examples are the steam engine, which led to the formulation of the laws of thermodynamics, and the microscope improved by Joseph J. Lister (father of the famous physician), which made bacteriology possible.[36] Such a feedback phenomenon is what makes the evolution of technology "Lamarckian."[37] It is this

[33]Acemoglu and Zilibotti (1997, p. 716) attribute with apparent approval to E.J. Hobsbawm the absurd statement that there was "nothing new in the technology of the British Industrial Revolution and the new productive methods could have been developed 150 years before." In fact Hobsbawm's statement (1968, p. 37) is that the Scientific Revolution cannot explain the Industrial Revolution because at the end of seventeenth century European "scientific technology" (sic) was potentially quite adequate for the sort of industrialization which developed eventually. It is still quite wrong, yet pointing this out does not deny that venture capital scarcity of the type emphasized by Acemoglu and Zilibotti and changes in its supply were of importance as well in determining the timing of the Industrial Revolution.

[34]For some attempts in this direction, see Mokyr (1998c, pp. 39-58).

[35]This is emphasized in Dyson (1997), pp. 49-50. The telescope drove the Galilean revolution just as X-ray diffraction to determine the structure of big molecules drove the DNA revolution.

[36]It is interesting to note that Carnot's now famous *Reflexions sur la puissance motrice du feu* (1824) was wholly ignored in France, and found its way second hand and through translation into England, where there was considerably more interest in his work because of the growing demand for this kind of insight on the part of the builders of gigantic steam engines such as William Fairbairn in Manchester and Robert Napier in Glasgow (Crosbie Smith, 1990, p. 329).

[37]The impact of technology on natural knowledge is stressed by Nathan Rosenberg (1982), though Rosenberg confines his essay to "science." Yet many elements in S are made possible through better techniques that we would not think of as "science" including for example the European discoveries of the fifteenth century, made possible by better ship-building and navigational techniques.

Lamarckian property that changed the dynamic nature of technological change during the Industrial Revolution and allowed for economic change to become the sustainable norm rather than the ephemeral exception.

A Knowledge Revolution

More or less contemporaneous with the Industrial Revolution was a revolution in what we would call today information technology.[38] The knowledge revolution affected the nature of S and through it the techniques mapped from it. Some of these changes were directly related to scientific breakthroughs, but from what I argued above it follows that what matters here is the advances in the organization, storability, accessibility, and communicability of information in S, as well as the methods employed in expanding it. The blossoming of open science and the emergence of informal "scholarly communities", spanning different countries in which scholars and scientists kept close and detailed correspondences with each other in the seventeenth century compounded these advances.

As a consequence, the amount of useful knowledge on which techniques in actual use could draw increased. In other words, the manipulation of natural processes and regularities in farming, engineering, chemistry, medicine and so on came to depend on increasingly complex natural knowledge. Even within a single firm the subset of S necessary to form the basis for the techniques used became so large that no single individual could carry them all. Thus the division of labor, much as Adam Smith thought, played a pivotal role in technological change, but it was not so much "limited by the extent of the market" as much as necessitated by the extent of the knowledge involved and the limitations of the human mind (Becker and Murphy, 1992). The growth of useful knowledge led to the rise of specialization in useful knowledge and the emergence of experts, consulting engineers, accountants, and thousands of other occupations controlling a particular subset of S. This meant that coordination between the activities of these specialists became increasingly necessary, and hence we have one more explanation of the rise of the factory system, the hallmark of the Industrial Revolution.

One aspect that is often overlooked is the speed and efficiency with which knowledge traveled. As Harris (1976, p. 173) has argued, much of the tacit, crafts-based knowledge spread through the continuous movement of skilled workers from one area to another. It is natural to think that the great discontinuity here

[38]This revolution is the subject of a new and exciting book by Professor Daniel Headrick (1998). I am grateful to Professor Headrick for allowing me to see his unpublished ms. on which much of the following is based.

occurred *after* the Industrial Revolution: the railroads in the early 1830s, the telegraph about a decade later. Yet as Rick Szostak (1991) has shown, the cost of moving about in Britain started to decline in the eighteenth century with the improved road system, ever more reliable stagecoach service, coastal shipping, and canals.[39] Moreover, it is by now recognized that the cost of and speed of the transmission of certain types of information was already declining before the telegraph. The Chappe semaphore telegraph, operating through France as well as in other parts of Western Europe, was a first step in this direction.[40] The Chappe system was a government monopoly and did not serve as a means of transmission of private information, yet it testifies to the age's increasingly rational and innovative approach to the transmission and dissemination of knowledge. The same is true for postal services: cross-posts (bypassing London) came into being after 1720, and by 1764 most of England and Wales received mail daily. Although the rates were high and their structure complex until Rowland Hill's postal revolution, which established the inland penny postage in 1840, postal services in England long before that were providing easy and reliable access to knowledge generated elsewhere. In the United States, as Richard John (1995) has shown, the postal service was a truly revolutionary agent. In 1790 each post office served 43,000 people, by 1840 each post office served only about 1,100 persons and for many years the postal service was by far the largest branch of the Federal government. Much of the post delivered consisted of newspapers.

Equally important is the standardization of information. For communication between individuals to occur, a common terminology is essential. Language is the ultimate General Purpose Technology, to use Bresnahan and Trajtenberg's (1993) well-know term. It provides the technology that creates others. Language is one way in which culture can affect the pathway from knowledge to technology and thus economic performance in the long run. It is a standard of efficient communication, necessary if people are to draw knowledge from storage devices and from each other. How important is language as a component of the kind of culture that eventually brings about economic development?

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[39]Merton (1970 [1938], pp. 216 ff) points out that by the end of seventeenth century a system of stagecoaches and postal service was already in operation, and argues that social interaction and the exchange of information were crucial to the development of science in this period.

[40]Under optimal conditions the semaphore system could transmit a bit of information from Paris to Toulon in 12 minutes in contrast with the two full days it would take a messenger on horseback. A 100-signal telegram from Paris to Bordeaux in 1820 took 95 minutes; in 1840 it took half as long. Given that a "signal" was picked from a code book with tens of thousands options, this was a huge amount of information. The optical telegraph at its peak covered 5,000 miles and included 530 relay stations.

The seventeenth and eighteenth centuries in Europe were the period in which technical and scientific writings switched from Latin to the various vernacular languages; thus even those without a classical education were given access. Of course, this reflects demand as much as cultural change. Either way, it marks the growing trend toward lower access costs that characterized Western European culture in the century before the Industrial Revolution.[41] To be sure, language and its use can adapt to changing circumstances, and Chinese writing today is quite different from the traditional *wen yen* or "written words."[42]

The language that came to dominate technical communications and thus "access costs" increasingly became the language of mathematics, the most widely cited consequence of the scientific revolution. It was associated more than anyone else with Galileo, who famously wrote that the book of the Universe was written in the "language of mathematics, without which it is impossible to understand a single word of it." Yet what counted is not just better and more useful mathematics, but also its accessibility to the people who might use it, engineers, instrument makers, designers, chemists, artillery officers, and so on.[43] In chemistry, such as it was, the scientific revolution created a movement in the direction of better comprehensibility and smoother communication, reducing access costs (Golinski, 1990) and its increasing quantification of the methods and language of chemistry in the eighteenth century made it increasingly accessible to potential users (Lundgren, 1990).

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[41]The importance of language as a communication tool and the need for a language designed along rational precepts modeled after mathematics, with exact correspondences between words and things was particularly stressed by Etienne Bonnot the Condillac (1715-1780), a central figure of the French enlightenment See for instance Rider (1990)..

[42]All the same, one of the most eminent Sinologists of our time, Derk Bodde, has made a startling argument in which he points to language as an impediment to the emergence and diffusion of scientific and technological knowledge. Bodde (1991) points out the inherent weaknesses of the Chinese language as a mode of transmitting precise information and its built-in conservative mechanisms. To summarize his views, Chinese language placed three obstacles in the way of the growth of useful knowledge in China. One was the large gap between literary Chinese and spoken Chinese. This made written documents far less accessible for people without considerable training and thus made it less easy for artisans and technicians to draw upon the useful knowledge accumulated by scholars and scientists. Second, the absence of inflection and punctuation created considerable ambiguity over what texts exactly meant. While Bodde's critics are right to point out that much of this ambiguity could be resolved if one knew the context, the point is that efficient communication must be able to provide as much information as possible with little context. Finally, Bodde points out that written Chinese was a formidably conservative force: it created a cultural uniformity over time and space that was the reverse of the dynamic diversity we observe in Europe. The way a nineteenth century official would describe Western barbarians was very similar in metaphor and illustration to the way this would be done by a Han statesman two millennia earlier (Bodde, 1991, p. 31).

[43]Arithmetics, of course, was an international language that could be understood by all. But more complex mathematics was changing the world as well. For instance, Mahoney (1990) points out that in the seventeenth century the mechanical view of the world and the formal science of motion changed dramatically because of the ability of mathematicians to represent it as differential equations of one form or another. This involved a dramatic change in the way mathematics was understood, yet once it was accepted it clearly represented a vastly superior way of representing relations between physical objects.

Another important component of such a system of communication is an accepted set of standards for weights and measures. During the eighteenth century technology gradually became more systematic about its reliance on quantitative measures (Lindqvist, 1990), and such a standardization became essential. Useful knowledge, much more than other kinds of knowledge, requires a strict and precise "I-see-what-you-see" condition to be communicated and transmitted. Mathematics was one such language, quantitative measures and standards another. The introduction of the metric system on the Continent during the French Revolution and the Napoleonic period, established a common code that despite some serious resistance eventually became universally accepted.[44] The United States and Britain chose to stick to their own system: in the eighteenth century most people used accepted measures of the pound, and the standard yard was made in 1758-60 and deposited in the House of Commons (Headrick, 1998, ch. 2). In 1824, Britain enacted the Imperial System of Weights and Measures codifying much of the existing system.[45] Such standardizations had been attempted many times before, but they required the coercive powers and coordination capabilities of the modern state.

Metrology was thus of considerable importance. The uniform organization of measurement and standards is a critical property of S if marginal access costs are to be kept low.[46] Many systems of codifying technical knowledge and providing standards were devised or improved during the Enlightenment. Headrick mentions two of the most important ones: the Linnaean system of classifying and taxonomizing living species, and the new chemical nomenclature designed by John Dalton and simplified and improved into its current form by Berzelius in 1813-14.[47] But other useful concepts were also standardized: In 1784 James Watt set the horsepower as the amount of energy necessary to raise 33,000 pounds one foot in one minute. Less well-known but equally important is the work of Thomas Young (1773-1829) whose modulus of elasticity

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[44] After some backtracking from the pure metric system as passed in 1799, the French government brought it back in full force in 1837; after 1840 it became the only legal system in France. See Alder (1995).

[45] Witold Kula (1986, pp. 117-19) has drawn a link between the enlightenment and the eighteenth century attempts to standardize measures, arguing that "disorder" of the kind caused by their proliferation could not be tolerated. While the reforms clearly had political and fiscal reasons, they led -- perhaps as a largely unintended by-product -- to a rationalization in knowledge-transmission.

[46] Latour (1990, p. 57) states with some exaggeration that "the universality of science and technology is a cliché of epistemology but metrology is the practical achievement of this mystical universality."

[47] Although the periodic table of elements was not finalized by Mendeleev till 1869, earlier attempts to represent the elements in an orderly and organized manner go back to Lavoisier himself. In 1817 a German chemist, Johann Döbereiner showed how the elements known at that time could be arranged by triads, encouraging others to search for further patterns. See Scerri (1998).

(1807) measured the resistance of materials under stress in terms of the pull in pounds that it would take to stretch a bar to double its original length.[48] There were even some attempts to quantify precisely the amount of physical work one man could be expected to do in a day (Ferguson, 1971; Lindqvist, 1990).

Of great importance to the streamlining of access to knowledge were what Ferguson (1992) has called "Tools of Visualization." The art of mechanical illustration was an early phenomenon and well established in the second half of the sixteenth century. Yet the great books of technical illustrations published at that time by Besson (1578) and Ramelli (1588) do not describe real existing machines as much as idealized concepts, and were lacking in visual perspective. Only the illustrations accompanying the *Encyclopédie* and the 80 volumes of the *Description des Arts et Métiers* (1761-1788) approached technical mastery. Ferguson (1992, p. 135) thinks that the impact of these volumes on stimulating technological change was "probably slight" and he is more inclined to attribute radical changes to the systematic works describing possible rather than actual mechanical movements such as Jacob Leupold's *Theatrum Machinarum* (1724-39). Ferguson thus underestimates the importance of access to knowledge of *existing* techniques as a key to their improvement and their recombination into novel "hybrids." In any case, the eighteenth century witnessed a great deal of progress in "technical representation," and by the middle of the eighteenth century technical draftsmanship had begun to be taught systematically (Daumas and Garanger, 1969, p. 249).[49] In addition, descriptive geometry was developed by the French mathematician Gaspard Monge between 1768 and 1780 (Alder, 1997, pp. 136-146) which made graphical presentations of buildings and machine design mathematically rigorous.[50] In Alder's words (p. 140), "it marks a first step toward understanding how the way things are made has been transformed by the way they are represented." The impact of Monge's sophisticated diagrams on the actual practice of engineering was probably modest at first, and technical drawings and orthographic projections were used by other engineers independently and long before Monge's work. My argument is simply that "the way things are represented" is a way of organizing S and that the visual organization of technical knowledge

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[48]Young's work was complex and poorly written and might have been forgotten in an earlier age. The Industrial Revolution era, however, had ways of disseminating important knowledge and his work found its way to the engineering community through the textbooks of Thomas Tredgold (widely read by engineers at the time), and articles in the Encyclopedia Britannica.

[49]Alder (1998, p. 513) distinguishes between three levels of mechanical drawing in pre-revolutionary France: the thousands of workshops where experienced artisans taught free-hand drawing to their apprentices; state-sponsored schools in which drawing teachers taught basic geometry; and the advanced engineering schools in which mechanical drawing was taught by mathematicians.

[50]Monge's technique essentially solved the problem of reducing three dimensional entities to two dimensions while at the same time depicting the relationships between the parts constituting the shape and configuration of the entity.

made enormous progress in the age of Enlightenment.[51] No doubt, Alder is right in pointing out that all such ways are "social constructions" and "cultural conventions," yet it is hard to deny that some social constructions lend themselves better to access and diffusion of knowledge than others. To be sure, no device can be reproduced from a drawing alone, and that when French engineers tried to assemble a Watt steam engine from a drawing prepared by him, the pieces did not always fit (Alder, 1997, p. 146). Yet such drawings clearly told people what could and had been done, and the mechanical principles on which it was based. No amount of dexterity and instinctive technical sense could make much progress without access to such knowledge. Moreover, Alder points out that these precise representations made standardization and interchangeability possible, and thus led eventually to the modularization characteristic of the second Industrial Revolution.

If the access costs are to be affordable so that production can draw on accumulated useful knowledge, there has to be social contact between "knowers" and "doers." There is too much tacit and uncodeable knowledge in technology for the written word and the graphical representation to do it all. Any society in which a social chasm exists between the workers, the artisans and the engineers on one side, and the natural philosophers and "scientists" (the word does not exist till the 1830s) will have difficulty mapping continuously from useful knowledge onto the set of recipes and techniques that increase economic welfare. If the *savans* do not deign to address practical problems where their knowledge could help resolve difficulties and do not make an effort to communicate with engineers and entrepreneurs, the *fabricans* will have difficulty accessing S. Within Europe, the depth of this chasm varied a lot (though nowhere was it totally absent).[52] Yet compared to China or classical antiquity it appears to be shallow. Above all, Britain was the country in which it may have been already the shallowest by 1700, and furthermore it was becoming shallower over the eighteenth

[51] In an interesting and iconoclastic paper, Latour (1990) attributes the emergence of modern science and technology to the representation of information in two-dimensional space where it can be manipulated and processed. He calls these representations "inscriptions" and points out that the role of the mind has been exaggerated, and that the mind's ability to process knowledge depends entirely on whether it has to deal with the real world or with these representations. At a less lofty but more sensible level, Alder (1998) argues that graphical representation was a mechanism to make "thick" (complex) reality into something "thin" (that is, comprehensible).

[52] Interestingly enough, the bridging of the social gap between the sphere of the learned scientist and that of the artisan was used by sociologists such as Zilsel to explain the origins of modern science, but with few exceptions has not played a similar role in explanations of the Industrial Revolution (see for instance Eamon, 1990, pp. 345-46; Cohen, 1994, pp. 336ff).

century.[53] The point is not whether engineers and artisans "inspired" the Scientific Revolution nor, conversely, whether the Industrial Revolution was "caused" by science. It is the strong complementarity, the continuous feedback between the two types of knowledge that set the system on a new course.

Personal and informal contact was naturally of primary importance in the eighteenth century. I have already referred to the scientific societies, academies, masonic lodges, coffeehouse lectures and other meetings. Some of those had the purpose of smoothing the path of knowledge between scientists and engineers on the one side and those who carried out the instructions and used the techniques on the other side. The circulation and diffusion of knowledge within S was equally important, and hence the importance of such bodies as the Royal Society and the Society of Civil Engineers founded by Smeaton in 1771. By the middle of the nineteenth century, there were 1,020 associations for technical and scientific knowledge in Britain with a membership that Inkster estimates conservatively at 200,000 (Inkster, 1991, pp. 73, 78-79).

Access to useful information also was determined by literacy and the availability of reading material. At least for Britain it is now widely agreed that increases in literacy were relatively modest during the Industrial Revolution (Mitch, 1998). Yet literacy is not all that useful unless people actually read, and for the purposes of technological change, it also mattered *how much* and *what* people read. At least two well-known inventions of the Industrial Revolution made the availability of reading material more widespread, the Robert method of producing continuous paper (applied in Britain by Brian Donkin around 1807) and the improvements in printing due to the introduction of cylindrical printing and inking using steam power invented by the German immigrant Friedrich Koenig in 1812. There is some evidence that with the development of lending libraries and the decline in the price of books, reading materials became more available.[54] Newspapers increased steadily in numbers and circulation, although the period of the Industrial Revolution was one of steady progress rather than quantum leaps forward (Black, 1994). I am not suggesting, needless to say, that people actually found technical descriptions in newspapers. The self-referential structure of S implies that before one can try to access knowledge, it is necessary to know that it actually exists or that

[53]Even the champions of Chinese science and technology have to concede that Chinese artisans were remarkably good at carrying out empirical procedures of which they had no scientific understanding. The real work in engineering was "always done by illiterate or semi-literate artisans and master craftsmen who could never rise across that sharp gap which separated them from the 'white collar literati'" (Needham, 1969, p. 27).

[54]An example is the gradual replacement of leather with cloth binding, making books "less aristocratic , less forbidding, less grand" (Manguel, 1996, p. 140).

a technique is used somewhere so that a search can be initiated. Here newspapers, magazines, and even "popular encyclopedias" played an important role. A part of the improvement in access technology resulted from an ability to ask better questions that were based on shards of knowledge. Without these shards, producers might not know what to look for. Asking the correct question and knowing whom to ask is more than half the way to getting to the answer.

Moreover, relevant and useful knowledge became more easy to access even for non-specialists. A major contributor to this was the growth of general purpose encyclopedias which had material arranged alphabetically or (in a minority of cases) thematically. Encyclopedias had been an old idea, and in 1254 Vincent of Beauvais completed his vast *Speculum*. By the time of the scientific revolution, the idea had caught on that existing knowledge could only be tapped if this knowledge was sorted and arranged systematically. Not surprisingly, the most eloquent call for such a project came from Francis Bacon himself.[55] The alphabetical organization of the material was first attempted in Louis Moréri's *Grand Dictionaire Historique* (1674). Fifteen years later Antoine Furetière published his issue of *Dictionnaire Universel des Arts et Sciences* (1690), which placed the kind of emphasis on arts and sciences that Bacon had called for. The first encyclopedia of what I termed "useful knowledge" in English appeared in 1704, John Harris's *Lexicon Technicum*, dealing with a host of technical issues. Its most prominent successor in English was Ephraim Chambers's *Cyclopedia,* first published in 1728, which went through many editions. Harris's book was perhaps the prototype of a device meant to organize useful knowledge efficiently: it was weak on history and biography, strong on brewing, candle-making, dyeing. It, too, contained hundreds of engravings, cross references and an index. It was, in Headrick's words, "a handy and efficient reference tool." The best example is Diderot's justly famous *encyclopédie,* the epitome of enlightenment literature, with its thousands of very detailed technical essays and plates.[56] As Headrick points out, the editors of the *encyclopédie* covered the useful arts in painstaking detail, visiting workshops, interviewing the most skilled craftsmen they could find.

[55]Bacon in his famous *Novum Organum* called for an organization of knowledge according to Platonic notions, much like his contemporary Mathias Martini (1606). His inspiration was acknowledged by the *encyclopédistes*: d'Alembert [1751], 1995, acknowledged "the immortal chancellor of England" as "the great man we acknowledge as our master" even if he and Diderot eventually chose a somewhat different way of organizing the knowledge (pp. 74-76).

[56]In the *encyclopédie,* in his article on "arts", Diderot himself made a strong case for the "open-ness" of technological knowledge, condemning secrecy and confusing terminology, and pleading for easier access to useful knowledge as a key to sustained progress." He called for a "language of [mechanical] arts" to facilitate communication and to fix the meaning of such vague terms as "light" "large", "middling" to enhance the accuracy of information in technological descriptions. The *Encyclopédie,* inevitably perhaps, only fulfilled these lofty goals very partially and the articles on technology differed immensely in detail and emphasis. For a recent summary of the work as a set of technological representations, see Pannabecker, 1998.

The approximately 72,000 entries included long ones on mundane topics such as masonry (33 pages), glassmaking (44 pages), and mills (25 pages). These essays were accompanied by many clear engravings. The *encyclopédie,* moreover, was a best-seller. The original version sold four thousand copies, but the total may have reached twenty five thousand copies if the many pirated and translated versions are counted, at an average of 30 volumes per set.[57] Diderot and d'Alembert's masterwork was widely imitated. The *Encyclopedia Britannica,* the most famous of these products in the English language, first appeared in 1771 as a fairly small project (3 volumes in 3 years) written by one person, William Smellie. It too focused on the sciences, useful arts, medicine, business and mathematics. Much larger editions soon expanded the range. German equivalents followed as well, culminating in the formidable *Brockhaus*, whose encyclopedia began appearing in 1809.[58] It remains to be seen if the encyclopedias and compilations were more than an expensive device by which a nouveau riche bourgeoisie demonstrated its intellectual imprimaturs for whom, in Headrick's words the technical essays constituted "intellectual voyeurism." At times, the knowledge contained in these compilations was already obsolete at the time of publication or became so soon after. In other cases, books about the useful arts were written by scholars to whom the esteem of the scholarly world was of first concern, and who were more inclined to cite past authorities than to examine with some care what was happening at the shopfloor (Harris, 1976, p. 169). Of course I do not argue that one could learn a craft just from reading an encyclopedia article (though some of the articles in the *encyclopédie* read much like cookbook entries). But they informed the reader of the dimensions and limits of S underlying 8 and once the reader knew what was known, he or she could look for details elsewhere.[59] The order of articles was organized in a form designed to minimize access costs: while alphabetization was not new, the idea of organizing useful information that way was quite radical.[60] This system, with its logical extension, the alphabetical index, must be regarded as the first search

57 Interestingly, the *encyclopédistes*, no more than Adam Smith, had any inkling of the imminent Industrial Revolution. The author of the article on *Industrie*, Louis Chevalier de Jaucourt, noted that Industry appears to have entered a stage in which changes are much more mild and the shocks far less than violent than before (Lough, 1971, p. 360).

58 Johann Beckmann, whose *Anleitung zur Technologie* (1777) was one of the first works to actually use the term, became Professor of Technology in Göttingen in the 1770s.

59 Thomas Blanchard in his 1820 application for a patent on his lathe, attributed the cam-motion that created irregular shapes to Diderot's *Encyclopédie* as well as to a depiction in the *Edinburgh Encyclopedia* (M.R. Smith, 1977, p. 125).

60 While not all encyclopedias or compendia followed this format, when they did not they became series of unrelated textbooks, less efficient for some purposes but still crammed full of relatively accessible knowledge. An example is Charles-Joseph Panckoucke's *Encyclopédie Méthodique*, a huge work conceived in the 1780s which over half a century published 166 volumes of text alone and many more of maps, plates, engravings.

engine, though by the time of the Industrial Revolution it was far from perfect as those consulting original editions of *The Wealth of Nations* can verify. It might be added that Chinese characters do not lend themselves to something akin to alphabetization and that the organization of useful knowledge in Chinese encyclopedias and compilations was awkward.

Other ways of cataloguing useful knowledge also emerged, especially in France. Encyclopedias were supplemented by a variety of textbooks, manuals, and compilations of techniques and devices that were somewhere in use. An early example was Joseph Moxon's 1683 *Doctrine of Handyworks*; the biggest one was probably the massive *Description des Arts et Métiers* produced by the French Académie des Sciences. Following the theoretical work of Monge and Lazare Carnot, the polytechniciens developed kinematics, a method of classifying mechanical movements by function, resulting in Jean Hachette's *Traité Élémentaire des Machines* (1808) and similar compendia. By the middle of the nineteenth century, reference books such as Henry T. Brown's *Five Hundred and Seven Mechanical Movements* (1868) had become quite exhaustive .

Of particular interest is the rise of statistics as a way of interpreting information about the physical world. The Newtonian view of the world was strictly deterministic rather than stochastic, and natural scientists were uneasy about the uncertainty it implied. It was readily realized, however, that a probabilistic approach was necessary for the formalization of empirical regularities in natural phenomena, the mechanisms of which were not fully understood or for which not all the information necessary was available.[61] The notion that empirical inferences could be made this way and that knowledge from large samples trumped personal experience no matter how detailed is another product of the enlightenment. Demography, medicine, crime and public health were obvious applications of statistics, but eventually they were applied to other areas in which they would prove useful, such as agriculture.[62] After 1815, statistics flourished, with statistical societies founded everywhere, and government all over the Western starting to collect more or less orderly statistical censuses and other types of information. It is this kind of empirical methodology that led to important breakthroughs in practical medicine, such as the reaction against bloodletting therapy spearheaded by the

[61]The insight that only an omniscient Supreme Being could dispense with probability because it had infinite knowledge but that human ignorance required some knowledge of the error term was first fully formulated by Laplace in the 3-volume *Théorie analytique des probabilités* (1812-20). See Porter (1986), pp. 71-73.

[62]One of the great private data collection projects of the time was Arthur Young's work in which he collected hundreds of observations on farm practice in Britain and the Continent -- although at times his conclusions were contrary to what his own data indicated. See Allen and Ó Gráda (1988).

statistical researches of C-A Louis and the discoveries that cholera and typhus are transmitted through water. These increments in S obviously mapped into some rather clear-cut techniques.

Did all this organization of useful knowledge matter? It is beyond question that the technological leaders of the Industrial Revolution, men like Smeaton, Watt, Trevithick, Roebuck, Wilkinson, Maudslay, and Roberts, were well-read in technical matters. So, by all accounts, were scores of lesser lights whose contribution, cumulatively, made all the difference. Moreover, in Britain many literate people, including entrepreneurs and peers in the House of Lords, possessed in Jacob's words "significant technical competence." How this familiarity with "science" and more widely with technical and useful knowledge precisely affected Britain's inventiveness remains a matter of some controversy. All codified knowledge surely needed to be complemented by tacit and implicit skills such as dexterity, a sense of "what worked" and so on.[63] But often such skills are directed and focused by knowledge acquired from others or from reading. For certain technical devices the knowledge that it worked *at all* or a very rough outline of how it did so sufficed for skilled engineers, physicians, chemists, or farmers. They could fill in the details.[64] The exact mapping from useful knowledge to technique took complex forms, and it is striking that France seems to have led Britain in terms of technical education, engineering textbooks, encyclopedias, and other access-cost-reducing developments.[65] Yet this observation does not refute the argument I made here. Britain's success in the Industrial Revolution was to a remarkable extent based on French inventions. From chlorine bleaching to gaslighting to Jacquard looms, Britain greedily looked to France for inspiration. To oversimplify to the point of absurdity, one could say that France's strength was in S, Britain's in 8, and that the mapping function bridged the Channel.[66] Perhaps the crucial difference between the two was in the way the political structures

[63]The importance of such tacit knowledge has been re-emphasized by Ferguson (1992), relying on the work of John R. Harris. The French had figured out that, as one mid eighteenth century French author put it, "eye and practice alone can train men in these activities." Yet tacit knowledge and formal visual or verbal knowledge should not be thought of as substitutes but as complements.

[64]Two cases of difficult access to *existing* stored knowledge are often cited. One is the existence of a copy of Vittorio Zonca's *Nuovo Teatro di Machine et Edificii* (pub. in 1620) in the open shelves of the Bodleian, unbeknownst to John Lombe who spent two years traveling in Italy to secure knowledge on the silk-throwing machine described therein he could have found closer to home. The other is the existence of a copy of Euclid's elements -- translated into Chinese -- in the Imperial library in the thirteenth century (Needham, 1959, p. 105), yet which apparently never noticed by the Chinese astronomers. The Zonca anecdote is usually cited as support for the importance of hands-on experience and personal observation, yet it is still unresolved whether a detailed prior knowledge of what the machine looked like and how it worked would not have greatly facilitated the Lombe's adoption.

[65]J.R. Harris (1976, p. 171) points out that there is more to be learned about coalmining – even British coalmining – from French sources than from English ones.

[66]For more details on the different scientific and technological trajectories of France and Britain, see Mokyr (1998c).

affected the mapping function. In France, engineering knowledge was mostly regarded as inspired by and in the service of national interests and political objectives, both on the part of those in control of the state and on the part of those wishing to undermine it. In Britain, overall, the subsets of 8 of interest to the engineers and scientists of the time were far more industrial and commercial. At the same time, the French government became aware very soon of its backwardness and took various measures to reverse what Jean-Antoine Chaptal called this "inversion of natural order" (cited by Jacob, 1998, p. 78). Chaptal, who was Minister of the Interior under Napoleon, was convinced that British industrial success was due to its superior "mechanical knowledge" and the close ties between the *savans* and the *fabricans* (Jacob, 1997, pp. 182-183). France's innovation in this regard, in addition to engineering schools, was the organization of industrial expositions, in which technical knowledge was diffused in an efficient and concentrated manner. These are merely differences of degree and timing, minor if we compare the West to Eastern Europe or the Middle East, but perhaps enough to explain much of the differences within Western Europe.

To repeat: the knowledge revolution of the Industrial Revolution was not just the emergence of *new* knowledge, it was better access to knowledge that made the difference. In some instances scholars have tended to overstate how much novelty had occurred in the centuries before the Industrial Revolution, minimizing its technological achievements.[67] To be sure, engineering knowledge during the age of the baroque had achieved some remarkable successes, and beside Leonardo a number of brilliant engineers and inventors are known to have proposed precocious devices: one thinks of Cornelis Drebbel, Simon Stevin, Giambattista Della Porta, Robert Hooke, Blaise Pascal, Gottfried Wilhelm Leibniz -- among many others. Yet their knowledge remained very difficult for subsequent rank-and-file engineers and mechanics to access, often presented to a selected audience or never published at all. The Enlightenment began a process that dramatically lowered these access costs. To return to the evolutionary framework, the knowledge revolution of the eighteenth century, that is, the changes in the structure of S, made the process of evolution more *efficient* in the sense that techniques that were superior spread faster because the ways they became known and could be tested improved. It is worth pointing out that such an increase in efficiency is *not* meaningful in a biological context, because there is no easy way to define "superior" independent of fitness (that is, the probability of being selected).

[67]Thus Ferguson (1992, pp. 63-64) states that a modern automobile engine contains mostly components that were known when Leonardo was alive, leaving electrical components and microprocessors aside. Yet the concept of the engine itself, transforming heat into work by burning fossil fuels was clearly absent in Leonardo's day.

Moreover, we should keep in mind that a substantial portion of invention consists of *recombination*, the application of a number of rather remote and disjoint sections of S together to form something novel. This is probably equally true today, and it is one of the chief reasons why access functions are so important in triggering the new mapping of techniques from S to 8. If taken to an extreme, such recombination can lead to dazzling rates of invention, because the rate of invention will be combinatorical, which is faster than exponential (Weitzman, 1996). Both Cort's puddling and rolling process and Crompton's mule were recombinations, but less famous examples are not hard to come by.[68] It may be an exaggeration to say with François Jacob that "to create is to recombine" (Jacob, 1977, p. 1163), as some elements were truly novel, but it surely is true that much of technological innovation consists of precisely such activities. Hence the extreme importance of efficient and accessible sources of useful knowledge in which one could check what was known about a particular natural phenomenon or process, or about techniques in actual use, and transfer them to novel applications.

Conclusion

I am suggesting that any historical account of economic progress, and above all accounts of the Industrial Revolution and its aftermath, need to incorporate *knowledge* explicitly. The much discussed "Information Technology" of our own age is one in which marginal access costs have been lowered enormously, and in many areas have been reduced to practically zero. The hardwired Internet II, which will be implemented in the next decade, will make current technology look archaic by comparison. This may be regarded as opening the floodgates to further technological progress in our age. The differences between the two episodes are at least as instructive as the similarities, and not too much should be made of such historical analogies. Perhaps the most striking conclusion to be drawn from it is that it is enormously difficult for contemporaries to realize how drastically their world is changing, what the important elements are, and how all this will work out in the future. The great economic minds of the age, from Smith to Ricardo, had only the faintest notion of the pending changes.[69] In a world of positive feedbacks, self-sustaining and self-reinforcing changes, and non-linear dynamics, in the words of Stuart Kauffman, "all bets are off."

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[68]Thus Richard Roberts' multiple spindle machine used a Jacquard-type control mechanism for the drilling of rivet holes in the wrought iron plates used in the Britannia tubular bridge (Rosenberg and Vincenti, 1978, p. 39).

[69]This is much less true for other writers of the time. For more details on the issue to what extent contemporary writers were unaware of the Industrial Revolution see Mokyr (1994c and 1998c).

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