serious scientific endeavor and eventually allowed Pasteur, Koch, and their disciples to refute spontaneous generation and to establish the germ theory, a topic I return to below. The germ theory was one of the most revolutionary changes in useful knowledge in human history and mapped into a large number of new techniques in medicine, both preventive and clinical. The speed and intensity of this interaction took place was still slow, but it was accelerating, and by the close of the eighteenth century it had become self-sustaining. In our time, new instrumentation has been an underestimated and unsung hero of advances in useful knowledge (Rosenberg, 1994).

A third way in which technology "fed back" into propositional knowledge was through the rhetoric of technology: techniques are not "true" or "false." Either they work or they do not, and thus they confirm or refute the propositional knowledge that serves as their epistemic base. **Q** -knowledge has varying degrees of tightness, depending on the degree to which the available evidence squares with the rhetorical conventions for acceptance. Laboratory technology transforms conjecture and hypothesis into an accepted fact, ready to go into textbooks and to be utilized by engineers, physicians, or farmers. But a piece of propositional knowledge can be also be tested simply by verifying that the techniques based on it actually work. Wedgwood felt that his experiments in the pottery actually tested the theories of his friend Joseph Priestley, and professional chemists, including Lavoisier, asked him for advice. During the nineteenth century, the general confidence in the **Q** -knowledge generated was reinforced by the undeniable fact that the techniques based on it worked. Thus, once biologists discovered that insects could be the vectors of pathogenic micro- parasites, 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 earn them wide support.

Had it not been for the cascading interaction between **Q** -knowledge and A-knowledge, the finiteness of the epistemic base would at some point have imposed a binding constraint on the expansion of the book of blueprints, as it had done in the past. Without a widening epistemic base, the continuous development of techniques will eventually run into diminishing returns simply because the natural phenomena can be understood only partially, and arguably only superficially. It is, of course, not easy to say precisely where the point of diminishing returns occurs. Complicating matters is that even when techniques rest on a fixed epistemic base, they can be recombined into compound techniques, and thus technological creativity can continue expanding even when the epistemic base was fixed—provided potential inventors have sufficiently inexpensive access to the catalog of techniques in use. All the same, if the epistemic base does not expand, technological progress will eventually slow down. Once the Q and ***X*** sets are subject to sufficient positive feedback, however, there is no way to predict the economic system's dynamics, and it may well diverge from its original state forever.[38]

That growing access to a common knowledge base was a catalyst in technological progress in the second Industrial Revolution cannot be proven rigorously, but a fair amount of historical evidence can be amassed to support it. An example is the simultaneity of many major inventions. The more a new technique depends on an epistemic base that is in the common domain and accessible to many inventors at low cost, the more likely it is that more than one inventor will hit upon it at about the same time. As useful knowledge became increasingly accessible and universal, it is hardly surprising that many of the inventions of the period were made independently by multiple inventors who beat one another to the patent office door sometimes by a matter of days.[39] Some scholars have suggested that the second Industrial Revolution rested as much on industry-based science as on the more common concept of science-based industry, implying feedback from $\boldsymbol{X}$ to Q (Konig, 1996).

As already noted, the *kind* of knowledge that was admissible as the basis for techniques and the mechanisms by which propositional knowledge could be verified and tightened also changed after 1830. An important element of the second Industrial Revolution was the growing recognition and admissibility of statistical evidence to establish natural regularities. Although the use of statistics has eighteenth-century origins, the growing legitimacy of statistical data as a source of useful knowledge can be traced back to the work of Adolphe Quetelet, Edwin Chadwick, William Farr, Villerme, and their colleagues in the 1820s and 1830s.[40] After 1815 statistics flourished, statistical societies were founded everywhere, and governments all over the West started to collect more or less orderly statistical censuses and other types of data. This kind of empirical methodology led to important breakthroughs in clinical medicine, such as the doubts regarding the efficacy of bloodletting therapy spearheaded by the statistical research of C. A. Louis and the discoveries that cholera and typhus are transmitted through water (Lilienfeld, 1978; La Berge, 1992). Statistical evidence (“data”) was a new investigative tool that made persuasion possible even if the underlying mechanisms were poorly understood. Natural regularities could be “tightened” by showing that they occurred in the majority of cases, even if there were unexplained outliers and the knowledge was “shallow” in the sense that the mechanisms accounting for the regularities were unknown. This approach led to an expansion of the epistemic base of public health. Villerme, Chadwick, and others showed that poverty was associated with higher morbidity and mortality (Hodgkinson, 1968; Mokyr, 1996). From there it was a natural step to techniques that prevented diseases from breaking out and reduced mortality long before effective cures had been found. Statistics was also used in the study of agriculture and the determinants of productivity, most famously at John Bennet Lawes's experimental farm at Rothamsted.

Beyond that, again, was the further level of interaction and feedback between human knowledge and the institutional environment in which it operates. Had institutional feedback been negative, as it had been before 1750, technological progress would have been short-lived. The economies that were most successful in the second Industrial Revolution were those in which the connections were the most efficient. The institutions that created these bridges are well understood: universities, polytechnic schools, publicly funded research institutes, museums, agricultural research stations, research departments in large financial institutions. Improved access to useful knowledge took many forms: cheap and widely diffused publications disseminated it. Technical subjects penetrated school curricula in every country in the West (although Britain, the leader in the first Industrial Revolution, lost its momentum in the last decades of the Victorian era). All over the Western world, textbooks, professional journals, technical encyclopedias, and engineering manuals appeared in every field and made it easier to “look things up.” The professionalization of experts meant that anyone who needed some piece of useful knowledge could find someone who knew, or who knew who knew. The learned journal first appeared in the 1660s and by the late eighteenth century had become one of the main vehicles by which **Q** -knowledge became accessible, if perhaps through the intermediation of experts who could decode the jargon. Review articles that summarized and abstracted the learned papers began appearing, an obvious example of an access-cost reduction.

The driving force behind progress was not just that more was known, but also that institutions and culture collaborated to create better and cheaper access to the knowledge base. Technology in the nineteenth century co-evolved with the new institutions of industrial capitalism. Institutional evolution in many ways followed its own dynamic. For instance, the repeal of the Bubble Act in 1825 was in large part the result of a power struggle between parties that believed they stood to gain from it (Harris, 2000). The creation of modern management ran into endless difficulties as documented in the late Sidney Pollard's still unsurpassed classic (Pollard, 1965). Yet on balance the feedback from technology to institutions was positive. Rent-seeking and unproductive behavior never disappeared in any human society, but in the years after 1815 in the West they were more and more subjugated by a free-market liberal ideology that provided incentives for entrepreneurial behavior which enhanced efficiency and productivity on a wide front. It is characteristic of competitive industrial capitalism as it emerged in those decades to spend effort and resources on microinventions and to make the new useful knowledge work (Baumol, 2002).

The co-evolution of technological knowledge and institutions during the second Industrial Revolution has been noticed before. Nelson (1994) has pointed to a classic example, namely the growth of the large American business corporation in the closing decades of the nineteenth century, which evolved jointly with the high-throughput technology of mass production and continuous flow. In their pathbreaking book, Fox and Guagnini (1999) have pointed to the growth of practically-minded research laboratories in academic communities, which increasingly cooperated and interacted successfully with industrial establishments to create an evergrowing stream of technological adaptations and microinventions. Many other examples can be cited, such as the miraculous expansion of the British capital market which emerged jointly with the capital-hungry early railroads and the changes in municipal management resulting from the growing realization of the impact of sanitation on public health (Cain and Rotella, 2001). But co-evolution did not always quickly produce the desired results. British engineering found it difficult to train engineers using best- practice Q- knowledge, and the connections between science and engineering remained looser and weaker than elsewhere. In 1870 a panel appointed by the Institute of Civil Engineers concluded that “the education of an Engineer is effected by…a simple course of apprenticeship to a practicing engineer.. .it is not the custom in England to consider *theoretical* knowledge as absolutely essential” (cited by Buchanan, 1985, p. 225). A few individuals, above all William Rankine at Glasgow, argued forcefully for more bridges between theory and practice, but significantly he dropped his membership in the Institute of Civil Engineers. Only in the late nineteenth century did engineering become a respected discipline in British universities.

Elsewhere in Europe, the emergence of universities and technical colleges that combined research and teaching, thus simultaneously increasing the size of Q and reducing access costs, advanced rapidly. An especially good and persuasive example is provided by Murmann (1998), who describes the co-evolution of technology and institutions in the chemical industry in imperial Germany, where the new technology of dyes, explosives, and fertilizers emerged in constant interaction with the growth of research and development facilities, institutes of higher education, and large industrial corporations with a knack for industrial research.[41] Institutions, then, remained a major determinant of access costs. To understand the mapping from **Q** to **A,,** we need to ask who talked to whom and who read what. Yet the German example illustrates that progress in this area was halting and complex; it needs to be treated with caution as a causal factor in explaining systematic differences between nations. The famed *technische Hochschulen,* the German equivalent of the French *polytechniques,* had lower social prestige than the universities and were not allowed to award engineering diplomas and doctorates till 1899. The same is true for the practical, technically oriented *Realschulen* which had lower standing than the more classically inclined *Gymnasien.* Universities conducted a great deal of research, but it goes too far to state that what they did was a *deliberate* application of science to business problems. James (1990, p. Ill) argues that Germany's "staggering supremacy" was not due to scientists looking for applicable results but came about "because her scientists experimented widely without any end in mind and then discovered that they could apply their new information." This seems a little overstated, but all the same we should be cautious in attributing too much intent and directionality in the growth of **Q** -knowledge. Much of it was in part random, and it was the selection process that gave it its technological significance. In that respect, the evolutionary nature of the growth in useful knowledge is reaffirmed.

A Third Industrial Revolution?

The half-century or so that followed the beginning of World War I is odd in at least three respects. First, it was a period of major political and economic upheavals that affected growth and productivity in many of the leading industrial countries, although in different ways. Second, as DeLong (2000) has recently reminded us, notwithstanding these disruptions, the twentieth century was a period of unprecedented growth. Third, much of this growth was technological in origin, yet true macroinventions were scarce in the period between 1914 and 1950 in comparison with the preceding decades. While science and useful knowledge in general kept expanding at an exponential pace, this era actually produced few radical new departures. Instead, a continuous flow of microinventions was the driving force behind much of the economic growth in the period 1914-73. The striking phenomenon here is that it took a very long time for these microinventions to start running into diminishing returns, and their effects on the productivity and thus on the standard of living were pervasive and ubiquitous. The main cause for the persistence and sustainability of technological progress was the widening of the epistemic base of techniques *already in existence* (some of them, admittedly, barely) in 1914, which created continuous opportunities for economic expansion and productivity growth.[42] When that base was narrow, as it was in pharmaceutics and synthetic materials, progress was halting and depended on serendipity. When that base was wider, as it was in mechanical engineering, electricity, and metallurgy, progress was relentless and continuous.

For many years, then, technological progress in the twentieth century followed the trajectories established in the years before 1914. In automobiles, chemicals, energy supply, industrial engineering, food processing, telephony and wireless communications, and synthetic materials, the developments after 1914 should be regarded as primarily *micro*- inventions. Microinventions tend to be the result of directed and well-organized searches for new knowledge, what the twentieth century has increasingly termed R&D.

Perhaps the most important development of the twentieth century is the change in the nature of the process of invention with the emergence of corporate, university, and government-sponsored R&D, what Mowery and Rosenberg (1998) have called the "institutionalization of innovation."[43]Whether individual independent inventors would eventually be made redundant by this development has been the subject of a long and inconclusive debate (Jewkes, Sawers, and Stillerman, 1969). A fair description of what happened in the twentieth century is that technology and the institutions on which it depended continued to co-evolve in the way I described above. In some industries, technological change may well have favored in-house research, particularly in the chemical and automotive industries, where large-scale facilities were all but indispensable. Yet the relation changed as the nature of technology and the environmental parameters changed. The twentieth century was the one century in which both the nature and the speed of technological progress were actively determined by politics. Governments invested in and encouraged research for strategic reasons.[44] Defense accounted for the lion's share of federal R&D in the United States, and the federal government financed a substantial proportion of R&D. In other countries, governments and other coordinating agencies were equally important. Much of the history of technology in the twentieth century can be described as a continuous search for the right "mix" of private and public efforts in R&D. The fundamental dilemma is well known to any economist: the private sector systematically underinvests in R&D because of the appropriability problems in the market for propositional knowledge. Government agencies, in both market and command economies, have done a poor job of picking winners, however, and have only haphazardly contributed to civilian techniques.

Despite the widely held belief that the twentieth century was qualitatively different from anything that came before (DeLong, 2000), much of the technology that deluged consumers with new and improved products and that accounted for unprecedented growth in total factor productivity was around—if in somewhat preliminary form—in 1914. As noted, the number of epochal macroinventions in the 1914-50 period was comparatively small. Nuclear power, of course, would rank at the top of those. It demonstrates that the minimum epistemic base for some technologies had become very extensive. Although quantum mechanics and nuclear physics were without doubt major expansions of the set of propositional knowledge, and the use of nuclear power a true discontinuity, nuclear power did not lead to the usual pattern of diffusion and microinventions. Improvements in the technique continued, but the costs of nuclear fission reactors in its fast breeder or thermal versions never quite became sufficiently low to drive out fossil fuels, and the safety and disposal problems have remained hard to solve.[45] More than any technology since the Industrial Revolution, nuclear power generation has become a target of political opposition (a topic I return to below). Nuclear fusion, which has the potential to produce limitless energy at low prices, has so far failed to become a reality except in hydrogen bombs. One might say that the minimum epistemic base required for handling materials at exceedingly high temperatures was not attained.

Quantum physics was less objectionable, perhaps because it was difficult to understand and its applications were less intrusive, at least at first. Much of the modern information and communication technology is in some way dependent on epistemic bases that belong to quantum physics. Tegmark and Wheeler reckon, perhaps somewhat heroically, that today an "estimated 30 percent of U.S. GNP is based on inventions made possible by quantum mechanics" including all microprocessors, lasers, and magnetic resonance imaging (2001, p. 69).

The other major macroinvention in the first half of the twentieth century was antibiotics (Kingston, 2000). It too followed a rather unusual path, but for quite different reasons. The minimum epistemic base for antibiotics to work was the knowledge that specific bacteria existed and that they caused diseases. Without the germ theory, Alexander Fleming's discovery of penicillin would not have taken place, since he would never have realized that his molds killed bacteria. Yet Fleming's discovery that certain molds were bactericidal and could be deployed in combating infectious disease was famously accidental. Fortune favored the prepared minds of Howard Florey and Ernst Chain, who purified and made possible the mass production of penicillin. Once the knowledge that antibiotics are feasible had been added to propositional knowledge, the development of other antibiotics followed. The epistemic base was still rather narrow: it is fair to say that no one had a very good idea precisely how antibiotics affected the germs they kill. Even the structure of the penicillin molecule was not fully understood until 1949. The way in which substances such as penicillin kill bacteria has been elucidated only in recent years leading to the possibility of replacing side chains of the molecule and thus overcoming bacterial resistance (Nicolaou and Boddy, 2001). Much work in pharmaceutics, even in the twenty-first century, still follows some systematic and computerized "try every bottle on the shelf' algorithm. The difference from other technologies was that antibiotics, much like insecticides, are subject to a negative feedback mechanism (the mutation of living species makes them immune to harmful substances), which after a while weakens their effectiveness. As a result, it is conceivable that the gains in the war against infectious diseases were temporary and that in the end humankind won a battle but not the war.

There were, of course, other major breakthroughs in the post-1914 decades. One thinks, for example, of the jet engine, catalytic cracking, and the emergence of man-made fibers and substances such as nylon. Many of these were, however, improvements upon *existing* techniques rather than totally new techniques.[46] These improvements and extensions (many of them, of course, major) became possible thanks to the continuous widening of the propositional knowledge on which they rested, but also because "modern science" made this knowledge tighter. Experimental and statistical methods to establish natural regularities and "causes" became more sophisticated, and new propositional knowledge, after being subjected to rigorous tests and critiques, when it became consensual, became the basis of searches for new prescriptive knowledge.

Perhaps the most discontinuous breakthroughs in the 1920s came in physiology. One of those was the discovery of insulin in 1922 and its extraction from animal pancreases, which made the treatment of diabetes possible. Another was the growing realization that trace elements (called vitamins in 1920) played a major role in preventing diseases that were recognized as caused by nutritional deficiency. The propositional knowledge about nutrition mapped directly into techniques employed by households in preparing food for their families, as well as by the food industry, which fortified products such as margarine with trace elements to ensure adequate intake.

Much of the progress in the first half of the twentieth century consisted of “hybrid” inventions, which combined components that had been worked out before 1914. The principles of the use of electrical power to run engines, activate vacuum tubes, and heat objects could be combined into radios, dishwashers, vacuum cleaners, fans, and virtually every other household appliance. Other pre-1914 inventions formed the basis of much industrial development until 1950 and beyond. The internal combustion engine and its cousin, the diesel engine—both up and running by 1914— eventually replaced steam as the main source of power.

The story of the chemical industry is a bit more complex (see Arora, Landau, and Rosenberg, 1998). Much of the chemical science underlying the synthetic materials industry was simply not around in 1914. A few synthetics such as celluloid and Bakelite were developed on a very narrow epistemic base.[47] Even so, some true macroinventions predate 1914.[48] Yet the advance of this industry into large-scale manufacturing of mass produced commodities such as nylon and polyester had to await the establishment of its epistemic base by Hermann Staudinger, who discovered the chemical structure of large polymers in the 1920s. The subsequent development of new materials depended crucially on this advance. The boundaries of chemicals expanded enormously in the inter- war years, into synthetic alcohol and fuels, paints, petrochemical organic feed stocks, new pharmaceuticals, and photographic materials (Murmann and Landau, 1998, p. 47). Yet the “golden age” of petrochemicals started only in 1945. The same dynamic holds for aerodynamics, where the epistemic base kept expanding as a response to technical successes, but which served as a further input into their design. The Wright brothers flew in 1903, a year before Ludwig Prandtl, the great theorist of aerodynamics, became a professor in Gottingen.[49] Only in 1918 did Prandtl publish his magisterial work on how wings could be scientifically rather than empirically designed and the lift and drag precisely calculated (Constant, 1980, p. 105; Vincenti, 1990, pp. 120-25). Even after Prandtl, not all advances in airplane design were neatly based on their epistemic base and derived from first principles, and the ancient method of trial and error was still widely used in the search for the best use of flush riveting in holding together the body of the plane or the best way to design landing gear (Vincenti, 1990, pp. 170-99; Vincenti, 2000).[50]

Much of the productivity increase in the twentieth century was the result of the perfection of production techniques and process innovation. Again, the roots of many of these ideas had been around in 1914, but the scale of organization and accuracy of detail continued to grow. These led to a continuous transformation in organizational methods, most obviously in mass production in manufacturing techniques but eventually in services and agriculture as well. For better or for worse, these changes have become known as “the American system of manufacturing” (actually their historical roots were complex), and their dissemination to the rest of the industrialized world was inevitable. It is perhaps a matter of semantics whether we think of these changes as “technological” or “organizational.” What matters is that they co-evolved with the ability of the capital goods industry to produce the tools and machinery that made their deployment practical, relying on an ever-growing epistemic base of materials and mechanical engineering.

The modernization of techniques can be broken down into several elements. The first is *routinization,* which made production processes interchangeable. Assembly, welding, painting, and packing all became increasingly similar for different products, a development with obvious implications for the specificity of human capital and skills. Another component was *modularization*, meaning that parts were identical up to a high level of tolerance and thus fully interchangeable. The advantages of modularization had been understood since Christopher Polhem enunciated them in the early eighteenth century, but the precision engineering that made it possible on an almost universal scale required machine tools that became available only in the twentieth century.[51] Modularization was closely related to *standardization*, making all products of a particular type conform to a uniform standard. Standardization, much like modularization, helped not just during the production stage of output but also in the maintenance of durable equipment. Whoever could repair one Model T could repair *any* Model T. It was also essential to mass marketing through catalogs and price lists. Mass production also entailed *acceleration* through continuous flow production. Continuous flow, in which the employer could determine the speed of each worker, could take place in production that involved assembly or disassembly (as in the stockyards), as well as for continuous physical and chemical processes (grain milling, refining).[52] Finally, in some applications there was a trend toward *miniaturization* (space-saving) such as in the design of smaller motors and steadily less clumsy microelectronics culminating in modern nanoelectronics.

Parallel with changes in the organization of production was the growing specialization of labor. Trends in specialization are complex: the routinization of production, as Marx already pointed out, was fundamentally de-skilling, and production employed undifferentiated homogeneous labor to perform simple tasks on machines that were increasingly user-friendly in the sense that they were easy to operate. Yet the division of labor became more and more refined in the twentieth century and led to a myriad of highly specialized occupations and tasks. The advantages of the division of labor and specialization have been commented on ever since Adam Smith wrote *The Wealth of Nations*.

Along with nuclear power and antibiotics, the most spectacular macroinvention of the twentieth century was the semiconductor.[53]Although all three emerged in the 1940s, electronics is the only area in which the continuous feedback between prescriptive and propositional knowledge, as well as recombination with other inventions led to a sustained and continuous growth that to date shows no evidence of slowing down and is believed by many to herald a “new economy.” Helpman and Trajtenberg (1998) have pointed to the semiconductor's unusual properties as an innovation: its ability to recombine with other techniques, its complementarity with downstream innovations, and its consequent pervasiveness in many applications, meriting the term general purpose technology (GPT). There have been few comparable macroinventions since the emergence of electricity in the late nineteenth century. A large cluster of separate inventions emerged, with an unusual propensity to recombine with one another and to create synergistic innovations that vastly exceeded the capabilities of individual components. Around 1955, vacuum tubes were replaced by the junction transistors invented by William B. Shockley a few years earlier.[54] In the 1980s and 1990s, such hybrid machines combined high-speed integrated circuits and then microprocessors with lasers, fiber optics, satellites, software technology, and new breakthroughs in material science and electronics that made high-density RAM storage possible. The so-called ICT (information and communication technology) revolution is not identical to the computer and was not implied by it, and many of the debates on the impact of "the computer" on productivity in the 1990s for that reason miss the point. Mainframe computers in the 1950s and 1960s and even the early personal computer (at first little more than a glorified typewriter and calculator) were not really a revolutionary general purpose technology, their many uses notwithstanding.

It always seems rash and imprudent when historians analyze contemporary events as if they occurred sufficiently long ago to be analyzed with some perspective. But the arguments made above suggest that the cluster of innovations around semiconductors and their applications will be viewed by future historians as a macroinvention; they represent the kind of discontinuity that separates one era from another, much like the two previous Industrial Revolutions. For a true technological watershed to take place, there has to be more than a GPT such as steam power or electricity or chemical engineering (Rosenberg, 1998a). There has to be a profound change in the generation and deployment of knowledge. The significance of the information revolution is not that we can read on a screen things that we previously read in the newspaper or looked up in the library, but that marginal access costs to codified knowledge of every kind have declined dramatically. The hugely improved communications, the decline in storage and access costs to knowledge, may turn out to be a pivotal event.

The significance of ICT is not just its direct impact on productivity but that it is a *knowledge technology and* thus affects every other technique in use precisely because it affects the level of access costs, which, as I argued in chapter 1, is one of the critical properties of Q. Given the huge dimensions that the set of propositional knowledge attained in the twentieth century (and its continuing exponential growth), ever-increasing specialization and narrow-based expertise are inevitable. The existence of search engines that allow an individual to find some known piece of propositional knowledge at low cost becomes critical, but other technologies to sort and assess the information to prevent overload are becoming essential. Indeed, it must be true that if useful knowledge had grown at the rate it did without changes in the technology of access, diminishing returns would have set in due to the difficulty in information management. After all, there is one immutable fixed factor: the human cranium. Although the flexibility of the human mind is remarkable, it remains true that the segment of total social knowledge that each person possesses is declining proportionally (even if it increases in total terms) over time. Specialization is the only way to deal with the current size of useful knowledge. An increasingly fine division of knowledge requires better and better access relations between people, and between individuals and storage devices. The Internet may seem to be the culmination of this process, but in fact access has been improving for decades in the form of computer-based information such as library catalogs, databases, and online access devices such as Medline. As some—if by no means all—of the people who carry out technological instructions (let alone those who write new ones) need access to more and more useful knowledge, the means by which they can find, access, sort, evaluate, and filter this knowledge is crucial.

That aspect of information technology holds the key to the future of technological creativity in our time. The uniqueness of the late twentieth century is that this body has become vast and depends on access-cost- reducing technology, without which it could never have advanced as fast as it did. The Internet and its "search engines"are but one element of this information revolution. Equally important is the institutional element: the establishment of social conventions of rhetoric and acceptability, coupled with growing professionalization and the formalization of expertise. The resource cost learning something is not the only variable that determines how easy access to knowledge is; there is also the matter of the reliability of the information.

Declining access costs are instrumental in the rapid diffusion of new techniques, not just because they cannot be employed before their existence is known, but also because in many cases each user has idiosyncratic needs and uses and has to adapt the technique to his or her specific conditions. This is surely true for agriculture, but it holds with equal force in the service industries and manufacturing. Someone executing a technique whose instructions were written elsewhere needs a way of answering specific questions that arise while actually implementing the technique, and these questions can often be answered using rapid and cheap communications.

Furthermore, falling access costs have stimulated technological progress through another phenomenon, technological hybrids and recombinations (what one might call technological compounds). If we consider each technique in ***X*** to be a "unit" of analysis, these units can interact with other units to produce entirely new entities. Most modern devices represent such compound bundles of knowledge, often scores or even hundreds of them.[55]

The notion that existing techniques can recombine into new ones is not novel (Weitzman, 1996), but in our framework it has deeper significance. It means that techniques can not only incorporate other techniques whole (which we might call "hybrids") but also import subsets of their instructions and their epistemic bases and combine these with their own (which would more properly be thought of as a recombination).[56] Hybrids and recombinations are not quite the same: there is a conceptual difference between joining together an internal combustion engine, a propeller, and a glider to make an airplane, and the application of mechanical knowledge underlying bicycle repairs in solving the specific problems that occur in airplane construction.[57] Either way, however, better access to knowledge not only will make it more likely that best-practice techniques are widely employed, but will also generate the emergence of such compound innovations.

But what, exactly, does "better access" mean? Even scientific knowledge in the public domain needs to be found, interpreted by specialists, and reprocessed for use. In recent years, economists have returned to Michael Polanyi's juxtaposition of tacit vs. codified knowledge (Cowan and Foray, 1997). Modern technology may be more codified and is thus more accessible by normal channels. In any event, even in the twenty-first century there is still a great deal of tacit knowledge that cannot be readily acquired from storage devices and can be accessed only by hiring the people who possess it. Nevertheless, modern ICT makes it easier to find the people who possess that tacit knowledge, and hire them, if possible, on an ad hoc basis. Technical consultants and subcontractors with "just-in-time expertise" have become pervasive. One reason, I suggest, is that modern ICT makes it easier to track down where this knowledge can be found (or, one step removed, easier to track down *who knowsvthzxt* this knowledge can be found, and so on).

Modern information technology has also produced new tools for conducting research, and thus an immensely powerful positive feedback effect from prescriptive to propositional knowledge. As I have argued repeatedly, a great deal of knowledge still consists of cataloging phenomena of great underlying complexity rather than coming to grips with their underlying mechanisms. Invention remains a pragmatic and empirical process of informed and systematic experiments, and looking what works. The process of drug discovery, although not as dependent on serendipity and intuition as it was in the age of Hoffman and Ehrlich, still often relies on "brute force" rather than on strategy. Molecular structures of proteins are so complex that the old and crude methods of search-and-see-what- works are still in place, albeit in a highly sophisticated form. Databases on genes, proteins, and their mind-boggling interactions require computer memories measured in petabytes (billions of megabytes). Molecular biology has expanded our knowledge of the natural world, and the modern pharmaceutic R&D based on it may well be called "guided discovery/' but it still represents a streamlined version of a traditional empirical discovery technique. Computers likewise have become indispensable in engineering. In the past, the difficulty of solving differential equations limited the application of theoretical models to engineering. A clever physicist, it has been said, is somebody who can rearrange the parameters of an insoluble equation so that it does not have to be solved. Computer simulation can evade that difficulty and help us see relations in the absence of exact closed- form solutions and may represent the ultimate example of Bacon's "vexing" of nature.[58] In recent years simulation models have been extended to include the effects of chemical compounds on human bodies. It is easy to see how the mutual reinforcement of computers and their epistemic base can produce a virtuous circle that spirals uncontrollably away from its basin of attraction. Such instability is the hallmark of Kuznets's vision of the role of "useful knowledge" in economic growth. Yet it would be as futile to search directly for these effects of ICT on national income statistics as it would be to search for the effects of the *Encyclopedie* on eighteenth-century French economic growth.

Useful Knowledge and Growth

The productivity and growth implications of revolutions in knowledge are at the core of much of the literature in the economics of technological change and productivity measurement. Oddly, however, economistshave not gotten into the "black box" of knowledge evolution in the past (with a few notable exceptions such as F. M. Scherer, Richard Nelson, and Nathan Rosenberg). Instead, total productivity measures generally take technological progress as exogenous. Models of endogenous growth have attempted to open these black boxes, but have just found another black box inside. The analysis of human knowledge as defined here takes a small step toward understanding what is inside this black box. As has been argued by many analysts in the evolutionary epistemology school (e.g., Plotkin, 1993; Wuketits, 1990) as well as by evolutionary psychologists (Nelson and Nelson, 2002), human knowledge can be and needs to be analyzed as part of a larger evolutionary paradigm. This effort was started in economics by Nelson and Winter in 1982, but so far has been little applied to economic history, where its marginal product seems particularly high.

The interaction between propositional and prescriptive knowledge grew stronger in the nineteenth century. It created a positive feedback mechanism that had never existed before, not among the scientists of the Hellenistic world, not among the engineers of Song China, and not even in seventeenth-century Europe. In that sense, Kuznets's insight is fully vindicated. The useful knowledge as it emerged in the decades after 1850 was truly *social* but the "society" in question was international—though not global. Societies that could overcome their own reluctance and the inertia of their institutions could "join the club," if at considerable cost. Japan and Russia, in very different manners, made that decision.

The economic history of knowledge suggests that an emphasis on aggregate output figures and their analysis in terms of productivity growth may be of limited use in understanding rapid growth over long periods. The full *economic* impact of some of the most significant inventions in the past two centuries would be almost entirely missed in that way. One reason for that has been restated by DeLong (2000). Income and productivity measurement cannot deal very well with the appearance of entirely new products. The Laspeyre index of income measures a basket from some year in the past and asks how much it would cost today; that is, comparing the current standard of living with that at some point in the past asks essentially how much *our* income would have bought then. But the whole point of technological progress is not just that goods can be made more cheaply. If that were all that was going on, such indices would measure progress accurately. In fact, new consumer goods not even dreamed of in an earlier age are making direct welfare comparisons otiose. In that regard we see a progression from the first to the second Industrial Revolution and even more into the twentieth century. The Industrial Revolution in the early nineteenth century created few new consumer goods, and consumption baskets in 1830 were not radically different from those in 1760. This was no longer the case in 1914, and by the end of the century new goods that satisfied needs hitherto unsuspected (Walkman radios, Internet service providers) or needs that simply could not have been satisfied earlier (laser vision-correction surgery) keep emerging at an accelerating pace. Traditional measures underestimate the rate of progress and do so at a rate that grows over time.

Moreover, goods become different, and they improve in ways that are very difficult to quantify.[59] Some aspects are difficult to quantify: reduced wear and tear, ease of repair and maintenance, and improved user- friendliness come to mind.[60] It has also been pointed out repeatedly that increased diversity and choice by themselves represent welfare improvements, and that modern technology makes mass customization possible by allowing customers to "design" their own final product from modular components (Cox and Aim, 1998).

[1]**The discovery of jasper by Josiah Wedgwood was based by experimenting on 10,000 trial pieces. McKendrick assesses that "every conceivable mixture was tried, every possible combination tested" (1973, p. 286). Yet Wedgwood instinctively felt that science would streamline this costly process, and if it were not materialized in his lifetime it would be the wave of the future.**

[2]**The way this came about was best described by the French chemist Claude Berthollet: "we are frequently able to explain the circumstances of an operation [that is, technique], which we owe entirely to blind practice, improved by the trials of many ages; we separate from it everything superfluous; we simplify what is complicated; and we employ analogy in transferring to one process what was useful in another. But there are still a great number of facts which we cannot explain, and which elude all theory. We must**