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Innovation in an Historical Perspective: Tales of Technology and Evolution

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2.1. Introduction

Are we living in the middle of an Industrial Revolution? The easy answer is, of course, that it is too soon to tell (Mokyr, 1997). Before a more specific argument can be made, it is essential to show what precisely was revolutionary about previous Industrial Revolutions and what elements made them so. Contemporaries of events that were at the start of what later turned out to be truly historical watersheds were not always cognizant of what was happening around them. The people alive during the first Industrial Revolution in the late eighteenth century were not fully aware of living in the middle of a period of dramatic and irreversible change. Most of the promises and future benefits of the technological changes were still unsuspected. Adam Smith clearly could not have much sense of the impact of the innovations taking place around him in 1776. Napoleon famously referred to Britain as a nation of shopkeepers, not of "cotton-spinners" or "steam-engine operators." By the time of the battle of Waterloo, however, this had already changed.[1] By the mid-nineteenth century, a growing awareness of the importance of technology in changing the world can be seen everywhere. Horace Greeley, the editor of the *New York Tribune,* pronounced in 1853 that "we have universalized all the beautiful and glorious results of industry and skill ... we have democratized the means and appliances of a higher life." These were to some extent prophetic words, since only the second Industrial Revolution brought technological progress to the advantage of the consumer. By the end of the nineteenth century, James P. Boyd, the author of *Triumphs and Wonders of the 19th Century, The True Mirror of a Phenomenal Era,* concluded that the invention and progress which have most affected the life and civilizations of the world, "the nineteenth century has achieved triumphs ... equal, if not superior to all centuries combined" (Smith, 1994: 5–7).

Terms like "revolution" tend to be overused and abused by historians. They draw attention. They sell books. But do they have historical content? In economic history, especially, melodramatic terms have a bad name, because the field tends to be relatively undramatic. Most of the things that play a role in modern economic growth are gradual, slow, and almost imperceptible: the dissemination of technological ideas, the accumulation of capital, even in most cases the changes in economic institutions were rarely very spectacular. In those cases in which a genu-

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[1] The Scottish merchant and statistician Patrick Colquhoun, only twenty-five-years Smith's junior, wrote in 1814 in a celebrated paragraph that "It is impossible to contemplate the progress of manufactures in Great Britain within the last thirty years without wonder and astonishment. Its rapidity, particularly since the French Revolutionary Wars, exceeds all credibility." At about the same time, the great manufacturer Robert Owen noted that "The manufacturing system has already so far extended its influence over the British Empire, as to effect an essential change in the general character of the mass of the people. This alteration is still in rapid progress ... This change has been owing chiefly to the mechanical inventions which introduced the cotton trade into this country ... the immediate effects of this manufacturing phenomenon were a rapid increase in the wealth, industry, population, and political influence of the British Empire." For details, see Mokyr (1998a: 3–5).

3rd IR –

inely dramatic invention occurred, its immediate impact on productivity was often negligible and if it occurred at all, took many years to be felt through the economy. The first Industrial Revolution used to be regarded as the most dramatic watershed event of the economic history of mankind since the invention of agriculture and has often been mentioned in one breath with the drama-laden contemporaneous French Revolution. It has now been shown to have had only minor effects on economic growth before 1815 and practically none on real wages and living standards before 1840, more than a century after the appearance of the first steam engine. The second Industrial Revolution, similarly, was slow in manifesting its full impact on the economies in question and it took much of the twentieth century to work out its effects fully. The paragon of the putative third Industrial Revolution, the computer, has still apparently not wholly lived up to the hopes and expectations regarding productivity and output.

It is ahistorical to think about Industrial Revolutions of any kind as a set of events which abruptly raise the rate of sustained economic growth by a considerable amount. Most of the effects on income per capita or economic welfare are slow in the coming, and spread out over long periods. Instead, we should recognize that even though the dynamic relation between technological progress and per capita growth is hard to pin down and measure, it is the central feature of modern economic history. We do not know for sure how to identify the technology-driven component of growth, but we can be reasonably sure that the unprecedented (and to a large extent undermeasured) growth in income in the twentieth century would not have taken place without technological changes. It seems therefore more useful to measure "industrial revolutions" in terms of the technological capabilities of a society based on the knowledge it possesses and the institutional rules by which its economy operates. These technological capabilities include the potential to produce more goods and services which enter gross domestic product (GDP) and productivity calculations, but they could equally affect aspects that are poorly measured by our standard measures of economic performance, such as the ability to prevent disease, to educate the young, to preserve and repair the environment, to move and process information, to coordinate production in large units, and so on. By those standards, it is hard to deny that the 1990s have witnessed an Industrial Revolution, but we need to assess it in terms of those capabilities, with the macroeconomic consequences, eventual but much delayed.

measuring IR **

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2.2. Knowledge and Economic Growth

Dramatic or not, technological progress has been the central driving force in modern economic growth. Historically this has not always been the case. Economic growth in pre-1750 was by no means always negligible, but it tended to be more heavily fueled by institutional change and the effects it had on trade creation and the allocation of resources. Processes such as improved property rights and better organized markets can create considerable wealth, and did so in various stages in Northern Italy, in England, and in the Low Countries. Technology had some striking achievements in the centuries before the Industrial Revolution, but all things considered, it probably accounted for limited growth.[2] The British Industrial Revolution (1760–1830) marks the first event in which changes in technology indisputably occupy the center of the stage due to an acceleration in the rate of innovation. Two other such accelerations can be tentatively identified: the "second" Industrial Revolution which started after 1860, and the closing decades of the twentieth century.

Whether such accelerations qualify these epochs for a "revolutionary" label remains a matter of semantics. The argument in this chapter is that these accelerations are neither complete accidents nor were entirely generated internally by inexorable factors such as market conditions or the institutional environment. Instead, we return to an argument made by

[2] The assessment of its role is complicated by the impact that technology had on the creation of markets and international trade through improvements in shipping and navigation.

Simon Kuznets (1965: 84–87). Kuznets wrote flat-out that modern economic growth was based on the growth of the stock of useful or "tested knowledge." He argued that "one might define modern economic growth as the spread of a system of production … based on the increased application of science." This seemed obvious to Kuznets because after all, "science is controlled observation of the world around us [whereas] economic production is manipulation of observable reality for the special purpose of providing commodities and services desired by human beings."

Few scholars would take issue with Kuznets's dictum that useful knowledge lies at the core of modern economic growth. In the past centuries too, additional factors were at work: capital accumulation, gains from trade, and improved factor allocations. Yet it is generally felt that without modern technology, Europe and the West might have ended up like China after 1800, when the gains from internal trade ran into diminishing returns and supporting institutions such as internal law and order were weakened by political instability. The exact definition of "useful knowledge" and how we approach its unusual dynamics in the past quarter millennium have barely been touched upon by economic historians.

Kuznets's definition, however, creates a dilemma for economic historians. It is agreed by historians of science and economics historians that the component of "science" properly speaking in the classical Industrial Revolution was quite modest, and that the tight interaction of scientific knowledge and engineering, applied chemistry, agriculture and so on postdate the middle of the nineteenth century. Even then, as discussed later, this connection remained quite tenuous in many fields. It is therefore obvious that Kuznets's transition from "useful knowledge" to "science" is not entirely satisfactory. Science was and is only a small part of what can be called "useful" knowledge. Useful knowledge includes *all natural phenomena and regularities* and, as such, it contains what we call science as a subset. It is true, perhaps, that by now most such regularities and phenomena that can be readily observed are known, so that any increments in the set of useful knowledge are likely to come from trained experts, but this is clearly a relatively recent development.

"Knowledge," as a historical factor, however, is a difficult concept. Epistemologists have for millennia argued about how we "know" things and what it means for something to be "known." Despite the central role that technology and human knowledge play in modern economic growth, economists have rarely spent much time worrying about the more subtle aspects of epistemology and probably rightly so. In technology, after all, we are not interested in whether something is "true" but whether it works. An invention based on a mistaken insight can at times enhance productivity and in that case the unsound foundation may seem immaterial. It would be impossible to understand the development of technology without realizing the knowledge and assumptions on which techniques rest. As an economic concept, knowledge is also slippery. It is a nonrival public good (sharing it does not reduce the amount available to the original owner), yet it is often excludable (it can be kept secret). Acquiring it can be costly to the individual, yet there is not much correlation between the costs of its acquisition and its marginal product. Knowledge does not follow simple rules of arithmetic and additivity, and it is highly self-referential (there is a lot of knowledge about knowledge). *New* knowledge's characteristics as a commodity have always been difficult to incorporate in a price-theoretic framework, and while certain kinds of patentable knowledge have come close, the patent system, even when it existed, has been notoriously uneven in its ability to protect and encourage new knowledge.

knowledge as club good

In recent decades, a growing number of scholars have argued that it is more enlightening to take an evolutionary approach to technological knowledge. This approach combines the evolutionary epistemology pioneered by Campbell and his colleagues with notions of "cultural evolution" and treats knowledge as produced by the system through a stock of information that is transmitted through time by "agents" who select and then "retain" (carry) it. The literature on this topic is quite large and growing rapidly. Surveys on the topic are readily available (Dosi and Nelson, 1994; Nelson, 1995b; Saviotti, 1996).

def'n – epistemic base

Can such an approach be used to shed light on the economic history of technological change? One way of applying this framework to economic history is to differentiate between *propositional* knowledge serving as background knowledge ("knowledge what") and *prescriptive* knowledge, which consists of "instructions" that constitute techniques or "routines" ("knowledge how to"). This distinction is neither original nor uncontroversial.[3] What is important is not so much to create taxonomies, as to realize that the relationship between these different kinds of knowledge was critical to the historical outcomes. Fundamentally, new techniques are created when in one form or another, useful knowledge is "mapped" onto a set of instructions which constitute a technique.[4] Much of this underlying knowledge maybe tacit and very poorly understood, but something has to be there for a technique to emerge. It is important to realize that this mapping involves a variety of agents, since the people who build artifacts and design techniques, much less those who carry them out, are not necessarily the ones who possess the knowledge. This means that *access* to propositional knowledge is as important as the amount known.

innovation

access

This setup leads directly to the concept of the *epistemic base* of a technique as that part of "propositional knowledge" of natural regularities and phenomena on which techniques in use are based (Mokyr, 2000). There is some minimum epistemic base without which techniques cannot be conceived, but for many techniques in use in 1750, this minimum may have been quite small.[5] The epistemic base *can* be much wider than the minimum: modern science knows a great deal more about the statistical mechanics of boiling water than is necessary to make a cup of tea. A narrow epistemic base of a technology that is in use means that people were able to figure out *what* worked, but did not understand *how* and *why* things worked. Further improvements, adaptations to changing circumstances, and new applications and extensions would be more difficult if the epistemic base was narrow. Further "research" would be encumbered by not knowing what does *not* work.[6]

The epistemic basis of a technique constitutes a "fixed factor" in the sense that continuous improvements in techniques in use without a growth in the underlying knowledge ran into something akin to diminishing returns. While it may not be *invariably* true that a deeper understanding of the physical processes at work is a sufficient condition for technological change to be self-sustaining, societies with little understanding of the processes they exploit would be limited in their progress.[7] There can

[3] The distinction between the two types of knowledge 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. Michael Polanyi (1962: 175) points out that the difference boils down to observing that knowledge "what" 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 patents inventions but not discoveries. The application of this dichotomy to the analysis of technological change was pioneered by Arora and Gambardella (1994) whose term for "useful knowledge" is "abstract and general knowledge" – although there is no particular reason why useful knowledge could not be both concrete and specific.

[4] There is a somewhat forced analogy between the dichotomy between the two types of knowledge and the distinction made between genotype and phenotype in biology. For a discussion of the merits and pitfalls of such isomorphisms, see Mokyr (1998b, 2000c).

[5] Some rather simple techniques might have an almost completely degenerate epistemic base, which means that the only knowledge on which they rest is that "this technique works." Such singleton techniques are discovered by accident or through exhaustive experimentation, and usually constitute dead ends in technological development.

[6] One thinks somewhat wistfully about the alchemical work of Newton (who wrote almost a million words on alchemy) and many other brilliant scientists such as Robert Boyle. Modern scholarship has shown that Newton, rather than being superstitious, was consistent with the best practice theories of his time (Brock, 1992: 30–32).

[7] When the natural processes at work are complex or misunderstood, progress can take place through a purely experimental approach, or by establishing exploitable empirical regularities through statistical techniques. Yet even such inductive-empirical methodologies of inquiry require epistemic bases such as statistical inference techniques.

be little doubt that the widening of the epistemic base in modern times was a critical element in sustaining technological progress. Nelson (2000: 74) has even maintained that "nowadays, of course, most technologies are understood, in part at least, 'scientifically'". *Understanding* a technique is, however, a relative concept: we may understand more about why certain techniques work than earlier generations, but we do not *really* know why physics and chemistry work the way they do either and we cannot be ontologically certain that our way of thinking about nature is the "right" or the only one (Cohen and Stewart, 1994). Such relativism, however, has its limits: for each technique there is some minimum epistemic base without which it cannot exist. This basis may not be *unique*, but it can grow and change, and as it does, it holds one key to the economic history of technological change.

One distinction used here is that between macroinventions and microinventions first introduced in Mokyr (1990b). The distinction between the two is largely based on the epistemic distance between them and the prescriptive knowledge previously available. A macroinvention is one that cannot be considered an improvement or an elaboration of existing techniques even though it, too, must rely on an existing epistemic base. The main characteristics of a macroinvention are an observable epistemological discontinuity from what was possible before. Over the years, biologists have changed their minds on the likelihood of such "saltations." The geneticist Richard Goldschmidt referred to them in a memorable term as "hopeful monstrosities" but it seems that even the believers in "punctuated equilibrium" no longer believe that biology can be *that* abrupt. In nature, "hopeful monstrosities" do not suddenly create new species.[8] There are points in the history of technology that we can identify as such hopeful monstrosities. One thinks instinctively of Newcomen's famous Dudley Castle 1712 steam pump, the "Silent Otto" (a monstrously noisy—its name notwithstanding—early version of the internal combustion engine), the first hot-air balloon, Babbage's difference engine, or even the ENIAC computer. We are interested in these cases precisely because we know what came before and after, and the huge leap represented by these machines and how they subsequently changed history.

ex's

One useful way to think about the economic history of technological progress is to think of it in terms of evolutionary trajectories that begin through a sudden novelty or macroinvention, which then are continuously improved and refined through a multitude of microinventions. Those myriad of small, incremental, mostly anonymous improvements and refinements that debug and modify the new idea so as to turn it into something workable and efficient, basically draw from the same or very close parts of the epistemic base. When this useful knowledge is exhausted, stasis is likely to set in until "punctuated" by a new macroinvention. It could be said that microinventions occur within an existing technological paradigm and are part of "normal technological change" whereas macroinventions require stepping outside accepted practice and design, an act of technological rebellion and heresy. Their success is in opening new doors, while microinventions fill gaps. In terms of their contribution to such economic variables as GDP growth and productivity increase, macroinventions are dwarfed by the effects of technological drift. But without great daring insights that represent a radical break of some sort with the past, such increments would inevitably grind to a halt.

Kuhn

2.3. The First Industrial Revolution

A renewed emphasis of "knowledge" in the first Industrial Revolution of 1760–1830 has been proposed recently in Mokyr (2000a). The

[8] See, for instance, Charlesworth and Templeton (1982). Yet none of that would contradict the commonplace observation that there are periods in which evolutionary innovation was very rapid and feverish, and others in which it proceeded, if at all, at a glacial rate. Perhaps, then, biological evolution did not have its steam engine or its mechanical clock, but it did have periods much like the Industrial Revolution in which change was unusually rapid, even on a different time scale. Such periods of "adaptive radiation" during which innovation was fast and radical have been documented at the beginning of the cenozoic with the spectacular proliferation of mammals (Stanley, 1981: 91–3.)

economic significance of the Industrial Revolution is not so much in the great gadgets that were invented in the "years of miracles" between 1760 and 1790, but rather that the process of innovation did not run into diminishing returns and peter out after 1800 or 1820. This is what had always happened in the past when Europe (or non-European societies) had experienced a cluster of macroinventions. The point is, above all, to explain why.

why prev tech progress petered out? (1)

There are at least two reasons for the failure of technological progress in the pre-1750 environment to generate *sustained* economic growth. One of them was institutional negative feedback. When economic progress took place, it almost always generated a variety of social and political forces that, in almost dialectical fashion, ended up terminating it. Prosperity and success led to the emergence of rent-seekers and parasites in a variety of forms and guises who eventually slaughtered the geese that laid the golden eggs. Tax collectors, foreign invaders, and distributional coalitions such as guilds and monopolies in the end extinguished much of the growth of Northern Italy, Southern Germany and the Low Countries.

cf. Rome, China etc

(2) The other reason is that before 1750, most techniques in use or known to be feasible rested on very narrow epistemic bases.[9] The famed inventions that formed the basis of the Industrial Revolution were accompanied by a deepening as well as a widening of the epistemic base of the techniques in use. Perhaps, by our standards, the direct technological achievements of the scientific revolution appear to be modest, and there is clearly much to recommend A. Rupert Hall's view that the early inventions of the Industrial Revolution lacked support in science proper (Hall, 1974). Yet, as I argued above, this is an overly restricted definition of the knowledge base of technology. Propositional knowledge included a great deal more knowledge that we would call "useful" but which was more artisanal knowledge than "science": examples are the lubricating qualities of oils, the hardness and durability of different kinds of woods, the location of minerals, the direction of the trade winds, and the strength and dietary needs of domestic animals. On the eve of the Industrial Revolution, with "science" in the modern sense in its infancy, this was most of what there was of the set of propositional knowledge.[10]

In the decades around 1800, advances in chemistry, mechanics, energy, material science, and medicine continuously expanded the informal and formal parts of useful knowledge, including—but not limited to—the well-known scientific advances of Lavoisier, Cavendish, Dalton, and their colleagues. This development was fueled by the self-propelled internal growth of propositional knowledge as well as by the feedback of technological breakthroughs into science and engineering. Before 1850, the contribution of *formal* science to technology was probably modest. Much of the technological progress in the first half of the nineteenth century came from the semi-formal and pragmatic useful knowledge generated by the great engineers of the Industrial Revolution: Maudslay, the Brunels, the Stephensons, Roberts, Neilson, and their colleagues. This does not really invalidate the argument that the interaction between propositional knowledge and prescriptive knowledge was the driving force behind technological expansion, only that we are missing most of the action if we concentrate our efforts on formal science. Two stereotypic cartoons, the one of an ignorant amateur "tinkerer" who stumbled into great inventions through a combination of inspired intuition and sheer luck, and that of the methodical, well-informed scientist whose rigorous papers inform applied scientists and engineers of the natural exploitable regularities are mostly

[9] In some areas, the epistemic base was reasonably broad but, by our standards, misconceived. Thus, eighteenth century metallurgy relied on phlogiston theory which, despite some useful implications, was shown to be false by Lavoisier. Much of medicine around 1750 still relied on the humoral theory of disease.

* some of epis. base wrong

[10] Many of the great discoveries of the Scientific Revolution were in areas that had little direct applicability such as cosmology and optics. This gradually began to change in the eighteenth century with the application of calculus to problems in hydraulic engineering and construction.

process

ahistorical. In between, there was a semi-directed, groping, bumbling process of trial and error with occasional successes, squeezing a messy, poorly defined blob of useful knowledge, some of it formal and codified, some of it simply passed on orally in terms of "this works and this does not" mapping into "here is how you do this."

(2) What made the difference between the innovations of the 1760s and 1770s, and those of the fifteenth century? As argued in detail in Mokyr (2000a), the scientific revolution and the enlightenment helped expand the epistemic base of techniques in use and thus create the conditions for more sustainable technological progress. Not only that, they expanded the set of propositional knowledge in a variety of ways; they also deepened it by making access to the knowledge easier and cheaper. This was in part a consequence of *social* access: the seventeenth century developed the notion of open science, published upon discovery. The social prestige of science and "useful arts" gradually increased over the eighteenth century in Britain, creating a closer connection between entrepreneurs and people with technical knowledge.[11] The eighteenth century also produced more efficient storage devices (textbooks, encyclopedias), search engines (indices, experts), and even improved and streamlined the language of technical communication. For an Industrial Revolution to produce sustainable technological progress, then, it requires not just new knowledge but the ability of society to access this knowledge, use it, improve it, and find new applications and combinations for it. As Headrick (2000) has stressed, the age of the Industrial Revolution through a variety of technological and institutional innovations did exactly that.

Besides the widening of the epistemic basis of technology, technology in the first Industrial Revolution co-evolved with the new institutions (1) of industrial capitalism. Institutional evolution in many ways followed its own dynamic. For instance, the repeal of the Bubble Act in 1825, as has been shown by Harris (2000) was in large part the result of a power struggle between parties that believed they stood to gain from it. The creation of modern management ran into endless difficulties as documented in the late Sidney Pollard's still unsurpassed classic (Pollard, 1965). Yet ultimately 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 which provided incentives for entrepreneurial behavior that on a wide front enhanced efficiency and productivity. Had institutional feedback been negative, as it had been before 1750, technological progress would have been on the whole short-lived.

How revolutionary was the Industrial Revolution? Modern economic historians have emphasized the continuities as much as the transformations. Steam engines looked and were spectacular, but water power continued to play an important role everywhere. Cotton was equally revolutionary, but the other textiles (wool, linen and silk) were much slower to change—although eventually they all did. Apparel making and millinery remained manual, domestic industries until well into the nineteenth century. The Cort process revolutionized wrought iron, but the making of cheap steel for industrial purposes remained out of reach until the 1850s. The great changes in industrial engineering—interchangeable parts, continuous flow processes, mass production of cookie-cutter standardized products—were all in the air at the time, but were not realized at an economically significant scale until the second half of the nineteenth

not revolutionary

[11] 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 nonproprietary 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. Margaret Jacob (1997: 115) has 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.

century.[12] Much of the British economy was affected very little until the middle of the nineteenth century; productivity growth was minimal and income per capita edged upward very slowly before 1830; real wages hardly rose until the mid-1840s.

revolutionary

The technological changes that occurred in Western Europe between 1760 and 1800 heralded a new age in the way that new instructional knowledge was generated. It was slowly becoming less random and serendipitous. This was the result of the widening of the epistemic base of technological knowledge, and improved access to propositional knowledge by engineers and entrepreneurs. As a result, the 1820s witnessed another "wave" of inventions which, while perhaps not quite as pathbreaking as the classic inventions of the "annus mirabilis" of 1769, created a second wind which prevented the process from slowing down. In the iron 1820s industry, for example, Neilson's hot blast (1828) sharply reduced fuel costs in blast furnaces, and the self-actor was perfected by Richard Roberts in the late 1820s. In energy production, the continuous improvement in engine design and transmission in the 1820s by a large team of engineers led to Stephenson's locomotive in 1828. Many of the important inventions of this period were anything but "serendipitous" but the result of more or less directed searches and concentrated efforts of informed engineers. Some of the ideas generated in this period, however, were not realized until after 1860, which is widely agreed to merit the title the second Industrial Revolution.

2.4. The Second Industrial Revolution

It is part of accepted wisdom that the techniques that came into being after 1860 were the result of applied science which had made enormous advances in the first two-thirds of the nineteenth century. In some industries this is surely true: one can hardly imagine the advances in the chemical industry after 1860 without the advances in organic chemistry that followed Von Liebig and Wöhler's work in the 1820s and 1830s.[13] Yet, as always, there was more continuity than is often allowed for. Invention by trial and error, luck, and instinct were not replaced entirely by a complete and full understanding of the natural processes at work. The two types of knowledge continuously kept reinforcing each other.

A full survey of the technological advances during the second Industrial Revolution is not possible here, but a few illustrative examples may help us understand the subtle interplay Stele between epistemic base and technique in this period.[14] Perhaps the paradigmatic industry of this period is steel; the breakthrough invention here, the Bessemer process of 1856, was made by a man who, by his own admission, had "very limited knowledge of iron metallurgy" (Carr and Taplin, 1962: 19).[15] His knowledge was limited to the point where the typical Bessemer blast, in his own words was "a revelation to me, as I had in no way anticipated such results." Yet the epistemic base was by no means degenerate: Bessemer knew enough chemistry to

[12] The famous Portsmouth block-making machines, devised by Maudslay together with Marc Brunel around 1801 to produce wooden gears and pulleys for the British Navy, were automatic and in their close coordination and fine division of labor, resembled a modern mass-production process in which a labor force of ten workers produced a larger and far more homogeneous output than the traditional technique that had employed more than ten times as many (Cooper, 1984). For an early application of the idea of interchangeability in France's musket making industry, see Alder (1997). The continuous flow process of the early mechanical spinning mills is emphasized by Chapman (1974).

[13] In organic chemistry, the pivotal breakthrough in the useful knowledge set was probably the understanding of the structure of the benzene molecule by the German chemist August von Kekulé in 1865, after which the search for synthetic dyes became simpler and faster. Benzene had been known for a few decades, and the first artificial dye had been synthesized a decade earlier by Perkin, so the discovery of the chemical structure counts as a classical broadening of the epistemic base.

[14] A more detailed survey can be found in Mokyr (1999), available in English on http://www.faculty.econ.northwestern.edu/faculty/mokyr/

[15] This example is also used by Arora and Gambardella (1994).

recognize that the reason why his process succeeded and similar experiments by others had failed was that the pig iron he had used was, by accident, singularly free of phosphorus and that by adding carbon at the right time, he would get the correct mixture of carbon and iron, that is, steel. He did not know enough, however, to come up with a technique that would rid iron of the phosphorus; this took another twenty years, when the basic process was discovered. Moreover, the epistemic base at the time was much larger than Bessemer's knowledge. This is demonstrated by the recognition, by an experienced metallurgist named Robert Mushet, that Bessemer steel suffered from excess oxygen, which could be remedied by the addition of a decarburizer consisting of a mixture of manganese, carbon, and iron. The Bessemer and related microinventions led, in the words of Donald Cardwell (1994: 292) to "the establishment of metallurgy as a study on the border of science and technology."

Energy utilization followed a comparable pattern. Engines in the sense we would recognize them today, that is, devices that convert heat to work in a controlled way, had existed since the first Newcomen machines, but the physics underlying their operation and governing their efficiency was not properly understood. A good intuition coupled with a sound experimental method were, up to a point, good substitutes for formal science and helped James Watt to transform a crude and clumsy contraption into a universal source of industrial power. Richard Trevithick, Arthur Woolf and their followers created, in the first decades of the nineteenth century, the more compact high pressure engine. But the science that established the efficiency of such engines did not exist. Perhaps typical of the division of labor between Britain and France, the first enunciation of the principles at work here—efficiency was a function of the differences in temperature—were laid out by a French engineer, Sadi Carnot, in 1824 after observing the differences in efficiency between a high pressure Woolf engine and an older model.[16] The next big step was made by an Englishman, James P. Joule who showed the conversion rates from work to heat and back. Joule's work and that of Carnot were then reconciled by a German, R.J.E. Clausius (the discoverer of entropy), and by 1850 a new branch of science dubbed by William Thomson (later Lord Kelvin) "thermodynamics" had emerged (Cardwell, 1971, 1994).[17] Yet this expansion of the epistemic base on which engines rested would have been irrelevant had it not led to applications in engineering which made old engines better as well as creating new ones. William Rankine, the author of *Manual of the Steam Engine* (1859) made thermodynamics accessible to engineers and Scottish steam engines made good use of the Carnot principle that the efficiency of a steam engine depended on the temperature range over which the engine worked.[18] One of Rankine's disciples, John Elder, developed the two-cylinder compound marine engine in the 1850s, which eventually sealed the victory of steam over sailing ships. An odd curiosum in this context is the somewhat obscure pamphlet published in 1862 by Alphonse Beau de Rochas which theoretically proved that the Carnot principles applied to all heat engines, and that the most efficient system would be a four-stroke cycle. Not long after, N.A. Otto started to work on an internal combustion gas engine, and in 1876 filed a patent based on the same four-

France vs England science

1850 thermo

otto

[16] Sadi Carnot, *Reflexions sur la Puissance Motrice du Feu* [1824], 1986. In his introduction, Fox points out that French technology was widely regarded to be behind British in all matters of power engineering, yet French engineering was distinctly more theoretical than British and there was a flurry of interest in the theory of heat engines. Carnot's work was incomplete and initially had little in it to be of help to engineers, but it was rediscovered by Thomson in the 1840s.

[17] Continuous work combining experiment and theory in thermodynamics continued for many decades after that, especially in Scotland and in Mulhouse, France, where Gustave Adolphe Hirn led a large group of scientists.

[18] Rankine did more than anyone in his time to bridge the gap between science and engineering by writing four textbooks that made the findings of the new science available to engineers. His *Manual of Applied Mechanics* went through 21 editions to 1921, and the *Manual of the Steam Engine* through 17 editions to 1908 (Cardwell, 1994: 335, 529).

stroke principle. Yet apparently the two were independent events.[19]

A third example of the widening of the epistemic base of technology leading to the emergence and then continuous improvement of techniques is the emergence of the telegraph. Many eighteenth century scientists, such as the great French physicist Coulomb, believed that magnetism and electricity were unrelated. But in 1819 a Danish physicist, Hans Oersted, brought a compass needle near a wire through which a current was passing. It forced the needle to point at a right angle to the current. It turned out that electricity and magnetism were related after all. Electro-magnetism, once discovered, was turned into a legitimate field of inquiry by the work of William Sturgeon, Michael Faraday and above all Joseph Henry who advised both the Englishman Wheatstone and the American Morse. The telegraph was associated with a string of inventors, the most important of whom were: S.T. von Soemmering, a German, who was the first to demonstrate its capabilities in 1810; William Cooke, an Englishman who patented a five-needle system to transmit messages (1837); and Samuel Morse, an American, who invented the code named after him that made the single-needle system feasible. The first successful submarine cable was laid by Thomas Crampton's Company between Dover and Calais in 1851, and became a technological triumph that lasted thirty-seven years. The idea of utilizing electrical current to affect a magnetized needle to transmit information at a speed much faster than anything previously possible was a classic macroinvention. Long-distance telegraph, however, required many subsequent microinventions. Submarine cables were found to be a difficult technology to master. Signals were often weak and slow, and the messages distorted. Worse, cables were subject at first to intolerable wear and tear.[20] The techniques of insulating and armoring the cables properly had to be perfected, and the problem of capacitance (increasing distortion on long-distance cables) had to be overcome. Before the telegraph could become truly functional, the physics of transmission of electric impulses had to be understood. Physicists, and above all Lord Kelvin, made fundamental contributions to the technology. Kelvin invented a special galvanometer, and a technique of sending short reverse pulses immediately following the main pulse, to sharpen the signal (Headrick, 1989: 215–218). In this close collaboration between science and technology, telegraphy was clearly a second generation technology.

macro

Yet it would be a mistake to suppose that all new technology during the second Industrial Revolution required broad bases in useful knowledge. The complex relationship between propositional and prescriptive knowledge is illustrated by the profound difference between two pathbreaking inventions of the second Industrial Revolution: aspirin (discovered in 1897) and electric generators (perfected between 1865 and 1880). Aspirin had a very narrow epistemic base. In 1763 a British clergyman, the Rev. Edmund Stone drew attention to willow bark which, he thought, would serve as a remedy against ague (malaria) because willows grew in damp places and God planted cures where diseases originated (Porter, 1997: 270). Not much was done with this "insight" until the 1820s, when chemists became interested in it once again. It was recognized that the active ingredient was salicin, and later the German Löwig obtained salicylic acid. While the chemical structure of these substances was known, they had little medical value because of severe side effects. These were eliminated when Felix Hoffman stumbled on the acetyl compound of salicylic acid, later known as aspirin. It was a true wonder-drug: effective, without serious negative side effects, and cheap to produce. His employer, Bayer, hit the jackpot. Yet no one knew how and why aspirin did what it did. It was not until the 1970s that aspirin's physiological modus operandi became more evident. With this extension of the epistemic base of

narrow
broad
bases

[19] Otto vehemently denied having any knowledge of Beau de Rochas's work, and given its limited diffusion, most scholars find that claim plausible (Bryant, 1967: 656).

[20] Of the 17,700 kilometers of cable laid before 1861, only 4800 kilometers were operational in that year – the rest was lost. The transatlantic cable, through which Queen Victoria and President Buchanan exchanged their famous messages in August 1858, ceased to work three months later.

an existing technique, further adaptations were possible.[21]

The refinement of electricity generation, on the other hand, could not make much commercial progress before some of the principles had been worked out. Faraday's narrow-based discovery of the dynamo demonstrated the possibility of generating electricity by mechanical means in 1831.[22] The technical problem with which engineers struggled for decades was the generation of electricity in quantities and at prices that would make it economically viable. The pioneers of the telegraph, Cooke and Wheatstone, patented the magneto in 1845. Joule had shown a few years earlier that the magneto converts mechanical energy into electricity (and not, as was believed until then, magnetism into electricity). The important implication of this insight was that the huge amount of mechanical power that the steam engines in the middle of the nineteenth century could create was convertible into electrical energy.[23] Although not all the physics underlying that had been worked out by 1865, Joule's work suggested how it could be done. A full generation after Faraday, the discovery of the principle of self-excitation in 1866–7 led to the construction of large generators in the early 1870s and eventually to the electrical revolution.[24] Yet the *exact* physical processes that underlie the generation of electrical power were not really understood until much later.

In short, after 1850, engineers in many areas increasingly engaged in "Research and Development" (the term is slightly anachronistic for the nineteenth century) that was less experimental and more directed. Many advances were made simply because the limitations of the narrow epistemic bases of old technologies were shed. This does not mean that there were no techniques in use that still rested on very narrow epistemic bases. But in industry after industry, the knowledge base expanded. The driving force behind progress was not just that more was known, but also that institutions and culture collaborated to create better, cheaper, access to the knowledge base.[25]

R&D *

The economies that were most successful in the second Industrial Revolution were those in which these 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, and research departments in large financial institutions. Improved access to useful knowledge took many forms: cheap and widely diffused publications disseminated useful knowledge. Technical subjects penetrated

[21] The pathbreaking work was carried out by John Vane, who showed how aspirin inhibited the formation of prostaglandins. Following this insight, other anti-inflammatory drugs such as ibuprofen were developed. See Landau, Achilladelis and Scriabine (1999: 246–51).

[22] The first working dynamo was constructed a year later by Hippolyte Pixii in Paris. Faraday himself oddly lost interest in the mechanical production of electricity soon after.

[23] Oddly, few physicists understood what Joule argued or took the trouble to try, given that he was a professional brewer and an amateur scientist. Fortunately, young William Thomson was one of the few who realized its importance and collaborated with Joule for many years.

[24] The self-excited electric generator was a classic case of simultaneous, independent invention by Werner von Siemens, Charles Wheatstone, C.F. Varley and others. The first working generators were constructed in the early 1870s by Z.W. Gramme.

[25] In the words of Charles Parsons (1911), the co-inventor of the steam turbine (1884), which revolutionized both marine propulsion and electricity generation, "In modern times the progress of science has been phenomenally rapid. The old methods of research have given place to new. The almost infinite complexity of things has been recognized and methods, based on a co-ordination of data derived from accurate observation and tabulation of facts, have proved most successful in unravelling the secrets of Nature … In the practical sphere of engineering the same systematic research is now followed, and the old rule of thumb methods have been discarded. The discoveries and data made and tabulated by physicists, chemists, and metallurgists, are eagerly sought by the engineer, and as far as possible utilized by him in his designs. the staff. In many of the best equipped works, also, a large amount of experimental research, directly bearing on the business, is carried on by the staff … it may be interesting to mention that the work [on the steam turbine] was initially commenced because calculation showed that, from the known data, a successful steam turbine ought to be capable of construction. The practical development of this engine was thus commenced chiefly on the basis of the data of physicists …"

good early R&D quote

school curricula in every country in the West, although interestingly enough Britain, the leader in the first Industrial Revolution was the laggard here. Textbooks, professional journals, technical encyclopedias, and engineering manuals appeared in every field, providing easier access to information. The professionalization of experts meant that anyone who needed some piece of useful knowledge could always find someone who knew how or where to find it.

As in the earlier period, the growing interaction between propositional and prescriptive knowledge took two basic forms. One was technical and concerned mostly the nature of knowledge itself. What is called here "useful" knowledge increasingly mapped into new techniques, but the positive feedback between the two types of knowledge led to continuous mutual reinforcement. This positive feedback took a variety of forms. One was that technology simply posed well-defined problems to the scientists and focused their attention on some areas that were well defined and turned out to be solvable. As noted above, thermodynamics emerged in part as an endogenous response to theoretical problems posed by the operation of the steam engine.[26] The other channel through which the feedback from techniques to useful knowledge worked was through improved instruments and laboratory equipment and methods.[27] Our senses limit us to a fairly narrow slice of the universe which has been called a "mesocosm": we cannot see things that are too far away, too small, or not in the visible light spectrum (Wuketits, 1990: 92, 105). The same is true for any of our senses and the computational ability of our brains. Technology consists in part of helping us to learn about natural phenomena we were not meant to see or hear by human evolution. Once these phenomena are known, they can provide us with ever more powerful tools to observe ever more remote phenomena; we can proceed to manipulate these further and so on.[28]

steam & thermo

The nature of what *kind* of knowledge was admissible as the basis for techniques 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. The use of statistics has eighteenth century origins, but the widespread use of statistical data as a legitimate source of knowledge can be pinpointed to the work of Quetelet, Chadwick,

[26] Less well known, but pointing very much in the same direction, is the interaction between the techniques of food canning and the evolution of bacteriology. The canning of food was invented in 1795, right in the middle of the Industrial Revolution, by a French confectioner named Nicolas Appert. He discovered that when he placed food in champagne bottles, corked them loosely, immersed them in boiling water, and then hammered the corks tight, the food was preserved for extended periods. Neither Appert nor his English emulators who perfected the preservation of food in tin-plated canisters in 1810 knew precisely why and how this technique worked, since the definitive demonstration of the notion that microorganisms were responsible for putrefaction of food was still in the future. The canning of food led to a prolonged scientific debate as to what caused food to spoil, a debate that was not finally put to rest until Pasteur's work in the early 1860s. Pasteur knew of course of Appert's work, and his work clearly settled the question of why the technique worked. In the terminology proposed earlier, the epistemic base of food canning became wider, and the optimal temperatures for the preservation of various foods with minimal damage to flavor and texture could be worked out.

food pres & Pasteur's germ theory

[27] This is emphasized by Dyson (1997: 49–50). The invention of the modern microscope by Joseph J. Lister (father of the famous surgeon) in 1830 serves as a good example. Lister was an amateur optician, whose revolutionary method of grinding lenses greatly improved image resolution by eliminating chromatic and spherical aberrations. The invention was used to construct a theoretical basis for combining lenses and reduced average image distortion by a huge proportion, from 19 to 3 percent. Lister was the first human being ever to see a red blood cell. This invention changed microscopy from an amusing diversion to a serious scientific endeavor and eventually allowed Pasteur, Koch and their disciples to refute spontaneous generation and to establish the germ theory. 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. Today's work in experimental biology would be impossible without X-ray crystallography and magnetic resonance imaging, to say nothing of powerful computers.

[28] As evolutionary theorists such as Vermeij (1993) and system analysts such as Kauffman (1995) have pointed out, dual systems that interact in such a way can reach a critical point, at which they become dynamically unstable and start to diverge from an equilibrium.

Farr, Villermé, and their colleagues in the 1820s and 1830s.[29] This work led to an enormous expansion of the epistemic base of medical techniques and to the identification of the causes of disease and their channels of transmission (Mokyr, 1996) and from there to techniques that prevented diseases from breaking out and reduced mortality long before effective cures had been found. By the beginning of the twentieth century, the theory of evolution had become widely accepted and genetics was rediscovered, and statistics found a variety of new applications, especially in the work of Francis Galton and Karl Pearson.

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, unclear where precisely the point of diminishing returns occurs. What complicates matters is that even when a large number of new techniques rest on a fixed epistemic basis, these techniques could recombine into compound techniques and thus technological creativity could continue expanding even when the epistemic base was fixed. Ultimately, however, if the epistemic base does not expand, technological progress will slow down.

The concept of growing access to a common knowledge base as 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 such 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 by a matter of days.[30]

Beyond that, again, was the further level of interaction and feedback between human knowledge and the environment in which it operates. The significance of 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 of such co-evolution, 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. 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 emergence of universities and technical colleges combining research and teaching.[31] The feedback between institutions and technology, as argued above, is not necessarily always positive. Technological success often creates vested interests that protect assets from being jeopardized by further invention. In the highly competitive and open economies of the second Industrial Revolution, however, such negative feedbacks were swamped by positive ones, and on the whole the institutions of mature industrial capitalism reinforced the growth of useful knowledge and vice versa. The complexity of two overlapping systems of positive feedback is immense, but it clearly is capable of producing continuous expansion.

[29] For some insights in the emergence of the statistical method in post-1830 Europe, see especially Porter (1986) and Cullen (1975).

[30] The phenomenon of independent simultaneous invention has often been interpreted as supporting the effect of demand conditions on the search for innovation, but obvious the ability of inventors to draw on similar bases in useful knowledge provides a complementary explanation. See Merton (1961) for a survey of the literature.

[31] 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 interested in industrial research.

2.5. A Third Industrial Revolution?

1914-1950

① upheaval

The thirty years or so that followed the beginning of World War I were odd in at least three respects. First, it was a period of major political and economic upheavals which affected the growth and productivity in many of the leading industrial countries, although in different ways. Second, as DeLong (2000) has recently reminded us, not withstanding these disruptions, the twentieth century was a period of unprecedented growth. Third, much of this growth was technological in nature, yet relative to what we may perhaps expect, there is a surprising scarcity of true macroinventions in the period between 1914 and 1973 compared to the preceding decades. While science and useful knowledge in general kept expanding at an exponential pace, it actually produced few radical new departures, and the ones that took place had a comparatively modest impact on the economy. Instead, a continuous flow of *micro*inventions was the driving force behind much of the economic growth, such as it was, in the period 1914–50. In automobiles, chemicals, energy supply, industrial engineering, food processing, telephony and wireless communications, and synthetic materials, the developments after 1914 fit this pattern. Micro-inventions tend to be the result of directed and well-organized searches for new knowledge, what the twentieth century has increasingly termed R&D. The striking phenomenon here is that it took a very long time until these microinventions started running into diminishing returns and their effects on the standard of living were pervasive and ubiquitous. The main cause for this 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, creating continuous opportunities for economic expansion and productivity growth.[32] When that base was narrow, as was the case in pharmaceutics and synthetic materials, progress was slow and depended on serendipity. When that base was wider, as was the case in engineering and metallurgy, progress was relentless and continuous. Yet by the definitions employed above, this progress does not qualify as an "Industrial Revolution."

② growth

③ ↑ tech but few macro inventions

micro from R+D

not an IR

As noted, then, the number of epochal *macro*-inventions 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. Quantum mechanics and nuclear physics were without doubt a major expansion of the set of useful knowledge, and the use of nuclear power was a true discontinuity: apart from occasional and fairly rare uses of tidal mills and geothermal heat, *all* energy had come from the sun. Nuclear power, however, did not lead to the usual pattern of diffusion and microinventions. While gradual improvements in the technique continued from the 1950s on, the costs of nuclear fission reactors in thermal or fast breeder versions never quite became sufficiently low to drive out fossil fuels and the safety and disposal problems have remained hard to solve (Victor, 2001). More than any technology since the Industrial Revolution, it has become a target of political opposition. Nuclear fusion, which had the potential to produce limitless energy at low prices, so far has failed to become a reality outside hydrogen weapons. One might say that the minimum epistemic base of handling materials at exceedingly high temperatures has not been attained.

①

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 germs existed and that they caused diseases. Yet Alexander Fleming's discovery that certain molds were bactericidal and could be deployed in

②

[32] Consider the following quote from a recent newspaper essay on the "New Economy": "The computer, of course, is at its heart—but not as a miracle machine spinning a golden future comparable to the industrial leap forward that came in the late 19th and early 20th centuries. Then, the electric motor, the light bulb, the internal combustion engine, petroleum, natural gas and numerous new chemicals all came on the scene—rearranging the economy and making it vastly more productive. The electric motor alone made possible the factory assembly line and mass production." Note that no such "industrial leap" is identified for the post-1914 period. See Uchitelle (2000b).

combating infectious disease was famously accidental. How and why they did so was unknown at the time. While fortune once again favored the prepared minds of Howard Florey and Ernst Chain, the modus operandi of antibiotics and much of the rest of our materia medica in existence was not understood when first employed and thus, in the terminology developed above, operated on a narrow epistemic base. The difference from other technologies was that antibiotics, much like insecticides, are subject to a negative feedback mechanism (due to the mutation of living species to make them immune to harmful substances), which after a while weakens their effectiveness and requires constant innovation just to keep the benefits from vanishing.

Between about 1950 and 1985, the pharmaceutical industry went through an unprecedented process of expansion. Yet much of this progress was attained on a narrow epistemic base. The industry developed a methodology known as "random screening" which is essentially a systematic application of the archaic "try every bottle on the shelf" principle. This method worked quite well, but it would eventually have run into diminishing returns had it not received a positive feedback shock from the growth in molecular biology from the mid-1970s on. As the cellular and molecular mechanisms of the operation of drugs became clearer, the screening method became more sophisticated and efficient. The expansion was further based, as Henderson et al. (1999) point out, on the sheer massive magnitude of unmet needs and research opportunities. Until 1950 medical science could cure few, if any diseases; the advances after that permitted cures as well as the alleviation of many symptoms.

DNA

Much as nineteenth century thermodynamics and chemistry provided the expansion of the epistemic base of the inventions of the Industrial Revolution and prevented it from fizzling out, the DNA revolution augmented the base of the pharmaceutical techniques developed in the 1950s and 1960s. It is this event, then, that is truly revolutionary in that it provided a means for technological change to avoid the trap of diminishing returns.[33] Pisano (2001) points out that this involved a change in the *methods* of R&D and refers to the phenomenon as the Molecular Biology *Revolution.* Genetic engineering took two rather distinct paths: the use of the new knowledge to improve the manufacture of substances whose modus operandi was already understood, and the use of advanced genetics in the discovery of new drugs moving from a process of more or less random discovery to one of "guided discovery."[34] Increasingly, we have the ability to *design* new drugs rather than *discover* them through recombinant DNA and monoclonal antibody techniques. As Evenson (2001) amply illustrates, the importance of this knowledge to agriculture is at least as important as in medicine. The importance of biological innovation in agriculture is not new (Olmstead and Rhode, 2000) but the developments in molecular biology promise solutions in pesticides and the use of marginal soils far beyond anything possible before 1970.[35] The truly revolutionary aspect, again, was not in the innovations themselves but in the creation of a useful knowledge base that made *sustained* innovation possible. In that regard, the revolution in cellular and molecular biology differed from that in nuclear physics. Yet they share the deepest common denominator of progress in the post Industrial Revolution technological era, namely a wide and widening epistemic base. Rather than the stochastic trial-

design vs discover

[33] For an excellent discussion, see Ruttan (2000). As he points out, the fundamental notion is not just that the DNA molecule contains critical information about life, but that microbes can exchange this genetic information. The breakthroughs in the applications of these insights occurred in the mid-1970s with the development of recombinant DNA by Cohen and Boyer and the fusion techniques developed by Milstein and Köehler.

[34] Henderson et al. (1999: 282ff). The authors point out that the two paths initially required quite different forms of industrial organization but have recently converged.

[35] Olmstead and Rhode demonstrate the possibilities of land-augmenting technological progress on a narrow epistemic base in the nineteenth century: through trial and error, it was discovered which varieties of vines were resistant to phylloxera, which parasites could be used to fight harmful pests, and how different varieties of wheat permitted the fine calibration of the growing season.

and-error method that characterized invention before 1800, progress is achieved increasingly by relying on a deeper understanding of the natural regularities at work.

"breakthroughs"

There were, of course, other major breakthroughs in the post-1914 decades: for example, the jet engine, catalytic cracking, and the emergence of man-made fibers and substances. Many of these were, however, improvements upon *existing* techniques rather than totally new techniques.[36] Perhaps the most discontinuous breakthroughs in the 1920s were in physiology: the discovery of insulin in 1922 and its extraction from animal pancreas which made the treatment of diabetes patients possible, and the growing realization that trace elements (termed vitamins in 1920) played a major role in preventing a series of diseases. The useful knowledge about nutrition mapped directly into a series of techniques employed by households in preparing food for their families, as well as the food industry which fortified products such as margarine with these trace elements to ensure adequate intake.

hybrid

Much of the progress in the twentieth century consisted of what we might call "hybrid" inventions, which combined components that had been worked out before 1914 in novel ways. 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 (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.[37] Even so, some true macroinventions predate 1914.[38] The chemical science underlying the technology co-evolved in classic fashion with the techniques. The same is true 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, moved to Göttingen.[39] Only in 1918 did he publish his magisterial work on how wings could be scientifically rather than empirically designed and the lift and drag precisely calculated (Constant, 1980: 105; Vincenti,

[36] The definition of a macroinvention does not exclude the possibility that the ultimate form the technique takes is the result of a number of discontinuous complementary breakthroughs. The best example is the steam engine, which arguably was not complete until the reciprocal (double-acting) cylinder and the separate condenser were added by Watt. It seems a matter of taste whether we would think of the jet engine and plastics in the same terms.

[37] Bakelite was patented in 1909 and manufactured on a commercial scale from 1910, but its chemical formula was not even established until 20 years later. Rosenberg (1998: 212) also points out that pilot plants were necessary simply because no body of scientific knowledge could answer the necessary questions.

[38] Of those, the technique to fix ammonia from the atmosphere perfected by Fritz Haber and his associates around 1910 must count as one of most momentous in modern history. Nitrates were the critical ingredient in both the fertilizer and the explosives industries and its fixation from the atmosphere had far-reaching consequences including the prolongation of World War I. Thermal cracking, which separates the long-chain hydrocarbons of petroleum into smaller but more important ones such as gasoline was first employed commercially in 1913 by Standard Oil researcher, William Burton. Catalytic cracking was developed by Eugène Houdry in the 1920s and speeded up the process considerably.

[39] Much of the knowledge in aeronautics in the early days was experimental rather than theoretical such as attempts to tabulate coefficients of lift and drag for each wing shape at each angle. The Wright brothers relied on published work (especially by Otto Lilienthal) available 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 that the Wright brothers were avid consumers of engineering science and that their greatness lay in the mapping function; however, before and even after their success, best-practice knowledge was limited.

1990: 120–5). Not all advances in airplane design were that neatly based on expansions of their epistemic base, and the ancient methodology 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 (Vincenti, 1990: 170–99) or the best way to design landing gear (Vincenti, 2000).[40]

Much of the productivity increase in the twentieth century, then, was the result of the perfection of production techniques and process innovation. Again, there was little truly new about the growth of these ideas beyond what 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 they were disseminated to the rest of the industrialized world. 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 based of materials and mechanical engineering.

The modernization of techniques can be broken down into a number of elements. The first is *routinization* which made production processes interchangeable. Thus, assembly, welding, painting, and packing all became increasingly similar across different products, with obvious implications for the specificity of human capital and skills. Another component was *modularization* meaning that identical parts were fully interchangeable. The advantages of modularization had been realized since Christopher Polhem 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.[41] Modularization was closely related to *standardization* meaning that all products of a particular type were identical. 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 could be assembly or *dis*assembly (as in the stockyards), as well as in continuous physical and chemical processes (grain milling, refining).[42] Finally, in some applications there was a trend toward *miniaturization* (space saving) such as in the design of smaller motors and less clumsy microelectronics resulting in modern nanoelectronics.

In parallel with changes in the organization of production was the growing specialization of labor. Trends in specialization are actually complex: the routinization of production, as Marx already pointed out, was fundamentally de-skilling, and production employed undifferentiated homogeneous labor, performing simple tasks on machines that were increasingly user friendly at least in the sense that their operation was simple enough. 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

[40] The hardening-process of aluminum in which the metal hardens slowly over the week following heating and quenching was discovered accidentally by Alfred Wilm in 1909 and eventually led to the use of aluminum in all aircraft construction. Metallurgists had a difficult time explaining the phenomenon of age hardening, but it took years until even a partial epistemic base had been uncovered (Alexander, 1978: 439).

[41] Hounshell (1984: 232–33) notes that by 1913, when Ford initiated his line assembly techniques, the machine industry was capable – perhaps for the first time – of manufacturing machines that could turn out large amounts of consistently accurate work.

[42] Von Tunzelmann (1995) who stresses the importance of time-saving technological changes, has identified at least four components of the speed of production: higher speed of operation, less down-time due to more reliable and easy-to-repair equipment, faster inter-process coordination, and faster intra-process coordination.

div of labor

have been commented upon ever since Adam Smith wrote his famous first chapter. His idea of the advantages of the division of labor were the growing familiarity of a worker with the process he is assigned to; his ability to produce improvements on it once he is thoroughly familiar with it; and the savings of time involved in moving from one task to another. The idea of the division of labor proposed by Smith was further picked up by Charles Babbage (1835: 175–6) who noted that specialization was not only useful for the reasons laid out by Smith, but also because workers had different inherent skill and strength endowments and it would be wasteful for employees to carry out tasks for which they were overqualified. An optimal matching of tasks to (exogenous) ability was a key to efficiency (Rosenberg, 1994: 28–9). A third argument for the division of labor is that with the growth of the knowledge base that each firm or plant needs to possess (its "core competence"), specialization is inevitable simply because the amount of knowledge is larger than one individual can possess.[43] This point was formalized and elaborated upon in a seminal paper by Becker and Murphy (1992), which suggested a new interpretation of the role of the firm. Given the limitations on what each worker can know, they maintain, the total knowledge that the firm has to possess is chopped up into manageable bites, divided amongst the workers, and their actions are then coordinated by management.[44] In addition to Smith's dictum about the division of labor being limited by the size of the market, the division of labor is limited from below by the size of the knowledge set that is necessary to employ best-practice techniques. The point is not just that each worker knows what he/she needs to know to carry out his/her task, but that he/she becomes in charge of a subset of the total knowledge required so that others can ask him/her when needed. This model predicts that when the amount of knowledge is small, plants can be small and coincide with households; when it expands it will require either a sophisticated and efficient network for the distribution of knowledge or a different setup of the unit of production (or a combination of the two). Modern manufacturing as it emerged in the twentieth century depended largely on the presence of in-house experts, not just in engineering, chemistry, and mechanics, but also in accounting, marketing, labor management, finance, and so on. Yet this setup is a function of the technology of the transmission of and access to knowledge.

The co-evolution of institutions and technology assumed new forms in the twentieth century.[45] 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."[46] A long and inconclusive debate emerged whether individual independent inventors would eventually be made redundant by this development (Jewkes, Sawers, and Stillerman, 1969). After 1945

[43] The "core competence" of a firm is different from the term "epistemic base" used here. An epistemic base is knowledge that has to be possessed by *someone* in an economy for a set of instructions to be written down. Actually carrying out such instructions involve quite different knowledge, just as inventing a bicycle, manufacturing one, and riding one all involve different kinds of skills and knowledge.

[44] A similar point is made by Pavitt and Steinmueller (1999: 15–16) in the context of the knowledge *generating* activities in the firm (that is, R&D). They point out that uncertainty and much tacit knowledge require "physical and organizational proximity" that guarantees efficient coordination of the knowledge-generating and the production and marketing functions of the firm. The skills involved in this coordination are themselves tacit and hence some meetings and personal contact remain important in industries that rely on a high degree of innovation; yet this does not mean that outsourcing to individuals working normally from other locations would not be effective.

[45] For a similar use of the term in the context of the computer hardware industry, see Bresnahan and Malerba (1999).

[46] Here, too, there were clear-cut nineteenth century roots. The great German dye manufacturers and large US corporations such as GE and Alcoa established the corporate research laboratory and the university as the prime loci where the technological frontier was pushed out, but the spread of this idea to the rest of the economy was slow and gradual.

circumstances favored a shift toward in-house research, particularly in industries such as chemicals and electrical equipment (Mowery, 1995). In-house research and inter-firm transfers of technology were to a large extent complementary but their shifting weight demonstrates the kind of institutional agility necessary for a successful co-evolution. Of particular importance, as emphasized above, is the connection between the people who know the science and those who map it into new techniques.[47]

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.[48] Defense accounted for the lion's share of federal R&D spending in the United States, and the Federal government financed a substantial proportion of R&D. In other countries, governments and other coordinating agencies played an equally important role in large part out of recognition of the likely failure of private research to provide the optimal mix and quantity of new useful knowledge, and in part for purely nationalist reasons. 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.[49] 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 useful knowledge and their failure to take into account the externalities involved. Government agencies, however, in both market and command economies have systematically done a poor job in picking winners and have only haphazardly contributed to civilian techniques. pub/priv balance

Capital markets provided another source of institutional agility. In the United States, venture capital markets emerged in the 1980s and 1990s and played a major role in the emergence of biotechnology, semiconductors, and software, among others (Mowery and Nelson, 1999: 363). Such institutions were almost unique to the United States, and explain its continued industrial leadership. The dynamic of modern technology, however, is that because of the openness and continued international transfer of technology, advances made in the United States due to better capital markets, patent protection, or another type of institution, were soon accessible to other nations. K

The 1940s witnessed the emergence of three spectacular macroinventions: nuclear power, antibiotics and the semiconductor.[50] While all emerged in the 1940s, electronics is the only area in which the continuous feedback between propositional and prescriptive 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 and 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 1940s

[47] It is telling that Henderson et al. (1999: 298) point to the institution most responsible for the success of American biotechnology as the "academic norms that permitted the rapid translation of academic results into competitive enterprises." Successful academics in biotechnology and computer science, among others, moved easily between the academe and the start-up, whereas elsewhere the ivory towers remained largely aloof from the technological revolution around them.

[48] Mowery and Rosenberg (1998: 28) note the irony in the post-1945 view that the great research projects of World War II (Manhattan Project, antibiotics, and synthetic rubber) demonstrated the capabilities of "Big R&D" to enhance social welfare.

[49] As Langlois (2001) points out, the modern computer combines the outcome of research initiated and financed by the government for computing machines with the private research efforts that led to the development of semiconductor technology.

[50] There are many excellent histories of the computer despite their obvious built-in obsolescence. See for instance Campbell-Kelly and Aspray (1996).

cf. semiconductors + electricity

late nineteenth century.[51] What has happened is the emergence of a large cluster of separate inventions with an unusual propensity to recombine with one another and to create synergistic innovations which vastly exceeded the capabilities of the individual components. Around 1955, vacuum tubes were replaced by the junction transistors invented by Robert Shockley a few years earlier. In the 1980s and 1990s, high-speed microprocessors combined with lasers, fiber optics, satellites, software technology and new breakthroughs in material science and electronics made high density ROM storage possible. The so-called Information and Communication Technology (ICT) revolution is not identical to the computer, and many of the debates on the impact of "the computer" on productivity in the 1990s miss the point for that reason. 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 GPT, their many uses notwithstanding. The 1990s witnessed the integration of microprocessors with scores of old technologies (such as household appliances) and new ones (cell phones, medical equipment). The ultimate impact of ICT, however, goes far beyond its ability to combine with other techniques.

It always seems rash and imprudent for historians to analyze contemporary events as if they occurred sufficiently in the past 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 not only as a macroinvention, but also as the kind of discontinuity that separates one era from another, much like the two previous Industrial Revolutions. For such a statement to be true, there has to be more than a GPT such as steam power or electricity or chemical engineering (Rosenberg, 1998). 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 in the decline of marginal access costs to codified knowledge *of any kind*. The hugely improved communications and the decline in storage and access costs to knowledge may turn out to be the pivotal event of the two closing decades of the twentieth century.

The significance of ICT, then, is not just in its direct impact on productivity but that it is a *knowledge technology* and thus affects every other technique in use. Given the huge dimensions that the set of useful knowledge has attained in the twentieth century (and its continuing exponential growth), ever-increasing specialization and narrow-based expertise is inevitable. Access in the form of search engines that allow an individual to find some known piece of useful knowledge at low cost becomes critical. Indeed, it must be true that had useful knowledge grown at the rate it did without changes in the technology of access, diminishing returns must have set in just due to the difficulties in information management on a gigantic scale. The segment of knowledge that each individual possesses is declining proportionally (even if it increases in total terms). An increasingly fine division of knowledge requires ever improving access relations between individuals, and between individuals and storage devices. It may be that Internet 2 will be the culmination of this process, but in fact access has been improving for decades now in the form of computer-based information databases such as computerized library catalogs, databases, and online access channels

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[51] The transistor is a good example of the concepts of knowledge employed in this chapter, as already noted in a classic paper by Nelson (1996). The epistemic base consisted of the natural regularity of the behavior of silicons as semiconducting materials, and the work of A.H. Wilson had explained this in terms of quantum mechanics in 1931. Much of the theory, however, was not fully understood until Shockley (1949) wrote his book in which he showed how and why the junction transistor would work. As Nelson remarks, "the theory was the invention" (Nelson, 1996: 170). Yet the continuous progress in computer technology could not have taken place without a wide epistemic base. Jean Hoerni's invention of the planar process, widely acknowledged to be the breakthrough that made progress in integrated circuits possible, could not have taken place without a thorough knowledge of the chemical and physical qualities of silicone (Langlois, 2001; Ceruzzi, 1998: 186).

such as Medline. As people who carry out technological instructions—let alone those who write new ones—have to access more and more useful knowledge, the means by which they can access, sort, evaluate, and filter this knowledge is crucial.

Above all, it is that aspect of information technology that holds the key to the future of technological creativity in our time. The uniqueness of the late twentieth century is that the body of useful knowledge has become vast, and that it has come to depend on access-cost-reducing technology without which it would never have advanced as fast as it has. If the Industrial Revolution witnessed an expansion of useful knowledge to the point where no *single individual* could possess it all and therefore growing intrafirm specialization was necessary, the closing decades of the twentieth century required far more than that. The internet and its "search engines" are one element in this. Equally important is the institutional element of the establishment of social conventions of rhetoric and acceptability, coupled with growing professionalization and the formalization of expertise.

Declining access costs are instrumental in the rapid diffusion of new useful knowledge, not just because techniques cannot be employed before the minimum epistemic base is available, 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 holds with equal force in the service industries and manufacturing. Hence, what a new user needs is a way of answering specific questions he or she has while actually implementing a technique, and it is these questions that can often be answered by rapid and cheap communications. The most effective and cheapest way to communicate is still to speak with someone in the same room, and the resurgence of the silicon valley industrial district is no accident. But ICT may in the end destroy its own parents: with the virtual reality implied in the high speed processing and huge bandwidth of Internet 2, many of the externalities in the generation of knowledge may soon become distance-independent, and concepts like the virtual industrial district are almost upon us.

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 to be a "unit" of analysis, much like in evolution these units can interact with other units to produce entirely new entities. Most modern devices represent such compounds, often scores or even hundreds of them.[52] The notion that existing techniques could recombine into new ones is not a novel one (Weitzman, 1993), 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).[53] Hybrids and recombinations are not the same: there is a conceptual difference between the combination of an internal combustion engine, a propeller, and a glider joining them together to make an airplane, and the application of mechanical knowledge underlying bicycle repairs in solving the specific problems that occur in airplane construction.[54] Either way, however, better access to knowledge will not only make it more likely that best-prac-

[52] The degree to which technology is "recombinant" can be approximated, however imperfectly, by the degree of citations to other patents and scientific literature in patent applications. Considerable research has gone into the topic of patent citations, and recent work shows that a fair number of citations take place to other patents that are reasonably unrelated. Unfortunately this information had to be attained from an ex post survey of the patentees and thus the inference is from a small sample and for 1993 only. It is striking, however, that, on a rank from 1 (unrelated) to 5 (closely related), 44 percent of the citations did not rank above 2. The data pertain to 1993 patents and therefore predate the Internet. See Jaffe, Trajtenberg, and Fogarty (2000).

[53] Just as we can define "general purpose technology" as techniques that can readily hybridize with others (electrical power being an obvious example), we can think of "general purpose knowledge" which maps into a large number of techniques and allows them to recombine. I am indebted for this point to Richard G. Lipsey.

tice techniques are widely employed, but will generate the emergence of these compound innovations.

But what, exactly, do we mean by "better access"? Even scientific knowledge in the public domain needs to be found, interpreted by specialists, and reprocessed for use. The most widely discussed issue is that of tacit versus codified knowledge (Cowan and Foray, 1997). It may or may not be the case that modern technology is more codified and thus is more accessible by normal channels. What is clear is that there is still a great deal of tacit knowledge, which cannot be readily acquired from storage devices and can only be accessed by hiring the people who possess it. However, 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 "just in time expertise" to whom specific tasks can be subcontracted out have become far more pervasive. One reason may be that modern ICT makes it easier to track down where this knowledge can be found (or, one step removed, who knows where this knowledge can be found, and so on). The problem, however, is not just access to knowledge but also its reliability. Knowledge supplied to us by strangers in a nonrepeated context could have serious verifiability problems. What needs to be explored is the impact of better ICT on the reputation mechanisms that protect users from false and misleading information, and to what extent the access technology will co-evolve with institutions that in one form or another permit users to assess its veracity.

2.6. Conclusions

If we are living in the middle of something we suspect future historians will regard as another Industrial Revolution, we need to define with some care what is meant by that. 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 enough, however, economists (with a few notable exceptions such as F.M. Scherer, Richard Nelson and Nathan Rosenberg) have not gotten much into the "black box" of knowledge evolution in the past. Models of endogenous growth have attempted to open these black boxes, but have just found another black box inside. Endogenous growth models analyze the production of new knowledge in terms of R&D and investment in human and physical capital, but they do not really bother with the epistemological issues of how knowledge is generated and communicated. Decomposing useful knowledge into its componenets as defined here and examining their interaction, as well as in Mokyr (2000a,b), takes a small step in the understanding of what is inside this black box. As has been argued by many analysts in the evolutionary epistemology school (e.g., Plotkin, 1993; Wuketits, 1990), 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 thus far has been little applied to economic history, where its marginal product seems particularly high. What is argued here is that the interaction between knowledge "what" and knowledge "how" created, under the right circumstances, an explosive dynamic that led to sudden surges in technology that we may call Industrial Revolutions. In the very long run, such surges have profound effects on economic growth and productivity, but the phenomenon itself should be analyzed distinct from its consequences.

[54] Many techniques can be identified as being particularly amenable to recombination. Historically in the West, watch making is probably the best example as a set of techniques with considerable spillovers of this kind. Watch-making knowledge was used in the making of instruments and fine machinery of all kinds and some watch makers made important inventions. The best-known inventors trained as clock makers were Benjamin Huntsman, the originator of the crucible steel technique, and John Kay (not to be confused with the inventor of the flying shuttle of the same name), who helped Arkwright in developing the water frame. Gunmaking played a somewhat similar role at some junctures, especially in the case of John Wilkinson whose boring machines helped Watt build his cylinders. In a modern context, Nelson (1996: 171) has pointed to the theory on which semiconductors were based as the source of better thermoelectric devices and the Bell solar battery.

This approach may also help in clarifying the role of institutions in the growth of technology in the past two centuries. Institutions play a central role in two different processes. One is the growth of useful knowledge itself, much of it motivated by purely epistemic considerations (i.e., curiosity about nature). The existence of organizations in which such knowledge is expanded, preserved, and diffused (such as academies, universities, research institutes, R&D departments) and the rules by which they play (such as open science, credit by priority, reproducibility of experiment, rhetorical rules, acceptance of expertise and authority), together with the perceived needs and priorities of the social environment in which they operate, help determine its historical path. The other is the mapping of this knowledge onto techniques. The institutions that play a role here are of course the usual ones that determine economic performance: incentives, property rights, relative prices. It should be stressed that through much of human past, the people who studied nature (natural philosophers and scientists) and those who were active in economic production (craftsmen, engineers, entrepreneurs) were often disjoint historical groups. Those who carried out the mapping needed to access the useful knowledge, and large social gaps between the *savans* and the *fabricans* were detrimental to technological progress.

Some nations were more attracted to the formal study of nature, while others were more inclined to look for applications. In the industrialized West as it emerged in the nineteenth century, a rough division of labor on the matter emerged.[55] Yet the free flow of information across national boundaries meant that American engineers could and did access French physics when they needed it and British manufacturers could rely on German and Belgian chemistry. This openness was enhanced both by institutions and technology. 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 historical experience of economic growth also suggests to modern economists that an emphasis on aggregate output figures and their analysis in terms of productivity growth may be of limited use if we are interested in its full impact on economic welfare and the quality of material life. The full *economic* impact of some of the most significant inventions in the last two centuries would be largely missed in that way. One reason for that was recently 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 have cost today; that is, comparing the standard of living at some point in the past asks essentially how much *our* income would have bought in terms of the goods available in the past. But the whole point of technological progress is not just that these goods can be made cheaper. New consumer goods not even dreamed of in an earlier age make such welfare comparisons useless. In that regard we see a progression from the first to the second Industrial Revolution and even more into the twentieth century. The first Industrial Revolution in the late eighteenth and early nineteenth centuries created few new consumer goods, and consumption baskets in 1830 were not radically different than in 1760. This was no longer the case in 1914, and by the end of the century new goods that satisfied needs unsuspected a century earlier (walkman radios, multivitamin pills, internet service providers) or needs that previously simply could not be satisfied (e.g., hip replacement surgery or telecommunication satellites) keep emerging at an accelerating pace. What that means is that not only do traditional measures underestimate the rate of progress, but they do so at a rate that grows over time.

DeLong

Moreover, goods become different, and improve in ways that are difficult to

[55] In the 1830s, De Tocqueville observed that Americans were not much interested in theory and the abstract parts of human knowledge. Rosenberg (1998b: 196) observed that this attitude was to characterize American culture for many decades to come.

measure.[56] Some of these aspects are almost impossible to quantify: reduced wear and tear, ease of repair and maintenance, and improved user friendliness come to mind.[57] It has also been pointed out repeatedly that increased diversity and choice by themselves represent welfare improvements, and that modern technology allows customers to "design" their own final product from modular components thus creating mass customization (Cox and Alm, 1998).

But more is involved than that.[58] Improved access to useful knowledge through electronic means implies that, insofar as the function of the firm (or, to be precise, the plant) is to facilitate communication between workers of different specialization, the ICT revolution means that geographical proximity is less and less required for such contact. We do not know to what extent the modern workplace as a separate entity from the household owes its existence to the need to exchange and access knowledge, but the sharp increase in telecommuting and telecottaging in recent years suggests a possible trend in that direction. If so, the welfare implications could be even more dramatic than DeLong suggests, since the social costs of commuting are a deadweight burden on society (much like any other transaction or trading cost), and because an enormous amount of capital in dwellings and buildings is inefficiently utilized by partial occupation, to say nothing of other social costs. It would be wildly optimistic to predict that within a short time ICT will reverse the effects of two centuries of economic change, but at the very least we could recognize that, aside from productivity, other dimensions of the nature of work are strongly affected by technological change and they affect economic welfare and performance in many unexpected ways.

telecommuting

[56] DeLong (2000: 7) chooses a particularly felicitous example. In 1895, a copy of the *Encyclopedia Britannica* cost US$35, whereas today a print version cost US$1250, about one-quarter in terms of labor cost. But a different good, the *Encyclopedia Britannica on CD ROM* today costs only US$50.00. How are we to compare the two? Assuming that in both cases, the content reflects an equally exhausting and reliable picture of the world, the CD ROM has some major advantages besides cost: it is easier to store, and access to information is faster and more convenient. It also includes more powerful imagery (through video clips) and audio. In short, readers in 1895 with a fast computer would have in all likelihood preferred the CD ROM version.

[57] This point is ignored in William Nordhaus's (1997) otherwise pathbreaking paper on the real cost of lighting. The true consumer gain from switching from candles or oil lamps to electric light was not just in that electric light was cheaper, lumens per lumens. It is also that electric light was easier to switch on and off, reduced fire hazard, reduced flickering, did not create an offensive smell and smoke, and was easier to direct.

[58] The following paragraph draws on Mokyr (2000b).